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EVALUATION OF SURFACE FRICTION GUIDELINES FOR WASHINGTON STATE HIGHWAYS

by

Patricia Corsello
LT, CEC, USN
University of Washington

Washington State Transportation Center (TRAC)
University of Washington, JD-10
The University District Building, Suite 535
1107 N.E. 45th St.
Seattle, Washington 98105-4631

Washington State Department of Transportation
Technical Monitor
Newt Jackson
Pavement and Soils Engineer, WSDOT

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ABSTRACT

The Washington State Department of Transportation (WSDOT) determines wet-pavement surface friction characteristics by conducting skid-tests in accordance with American Society for Testing and Materials (ASTM) Method E-274. The results of the skid-tests, Friction Number (FN), are used as one of several variables in programming safety improvements.

This report examines literature from the United States and abroad on friction number guidelines for highways. On the basis of an analysis of the literature, a revised friction number guideline was developed. The new guideline is consistent with other highway departments that have recently reviewed their minimum friction number guidelines. Most importantly, the new guideline provides WSDOT pavement engineers with a realistic parameter for assessment of highway pavements.

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This study was conducted at the University of Washington under the supervision of Professor Joe P. Mahoney. The work was performed by Lt. Corsello in partial fulfillment of the MSE degree in the Department of Civil Engineering. The WSDOT technical monitor was Newton C. Jackson.

16. ABSTRACT

The Washington State Department of Transportation (WSDOT) determines wet-pavement surface friction characteristics by conducting skid-tests in accordance with applicable AASHTO and ASTM standards. The results of the skid-tests are used in conjunction with other criteria to assist in selecting pavements for resurfacing (the primary criteria is wet-pavement accident rates).

This paper examines literature from the United States and abroad on friction number guidelines for highways. On the basis of an analysis of the literature, a revised friction number guideline was developed. The new guideline is similar to those developed by other highway departments and is based on research conducted over the last 25 years.

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DISCLAIMER

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CHAPTER 1

INTRODUCTION

BACKGROUND

The earliest research report on the skid resistance of rubber tires on various road surfaces was presented at the 1933 annual meeting of the Highway Research Board by Ralph A. Moyer. (15) The report gave a true indication of the many variable factors that influence tire and road friction, especially the hazardous, slippery conditions of certain road surfaces when wet. Moyer discovered that coefficients of friction for all slippery surfaces, except those covered with snow or ice, are fairly high at low speeds, but drop sharply as the speeds of vehicles increase, as shown in Figure 1. Furthermore, Moyer noted that the seriousness of the hazard created by slippery road surfaces becomes more apparent when attention is directed to the fact that the friction requirements for driving operations, such as acceleration and braking, increase approximately with the square of the speed. (16) These concepts are shown graphically in Figure 2. (1)

The phenomenal increase in the volume and speed of highway traffic after World War II was accompanied by a similar increase in the occurrence of highway accidents. Since World War II, many factors believed to contribute to these accidents have been studied. Most researchers agree that these factors fall into three major categories: (a) the driver's behavior, (b) the roadway and its environment, and (c) the vehicle and its characteristics. (3) Highway departments concentrate on the roadway and its environment, with safety and economics among their highest priorities. This report focuses on wet-pavement skid resistance. It specifically examines the issue of minimum skid resistance guidelines for highways. These guidelines are designated to ensure that adequate friction is available in wet conditions.

Minimum skid resistance guidelines have been the focus of intensive research efforts since the National Highway Safety Act of 1966, which requires states and jurisdictions to maintain the skid resistance of public highways and streets. "Maintain" includes correction of excessive slipperiness. (1)

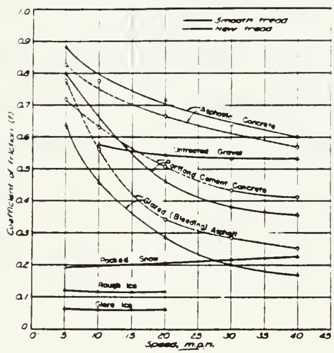

Figure 1. Coefficients of Friction for New Tread and Smooth Tread Tires on Various Types of Road Surfaces in Wet Condition (Moyer [16])

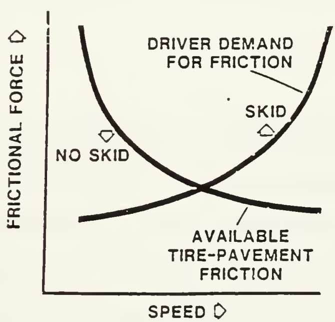

Figure 2. Available Friction and Driver Demand (Byrd et. al [1])

In the mid-1960s, Kummer and Meyer (12) performed a landmark study to determine frictional requirements for main rural highways. The study was published in 1967 by the Highway Research Board (HRB) as National Cooperative Highway Research Program (NCHRP) Report 37. The report recommended a minimum skid number of 37 for the national road network, as measured with a skid trailer in accordance with ASTM Method E-274. The HRB emphasized that the recommended skid number was minimum and tentative and that specific frictional requirements needed to be determined for each given set of road, vehicle, operator, and weather conditions. The HRB suggested continued research to develop a more refined skid resistance requirement. (12)

Since 1967, researchers have made significant progress in field and laboratory methods of measuring road surface friction, comparison and correlation of the different measuring methods, relationships of road surface properties to skidding accidents, and several other aspects of the tire-pavement interaction. This report adjusts the skid number recommended by HRB in 1967 to reflect these research developments.

Before analyzing specific adjustments to the minimum skid number, basic principles are briefly discussed.

SKID RESISTANCE

When a pavement is wet, quick braking or turning maneuvers may cause a vehicle's tires to slide because of the lower friction between the tires and the pavement. In this report "friction" is understood to be the force developed at the tire-pavement interface that prevents the tires from sliding on pavement surfaces under fast braking or cornering. The term "skid resistance" has also been used to describe this tire-pavement interaction. The two terms (friction and skid resistance) are used interchangeably in this report, as they are in the literature.

Skid resistance can be stated several ways: coefficient of friction (μ), Friction Number (FN), or Skid Number (SN). Each is defined as follows:

a. Coefficient of Friction (μ)

$$\mu = \frac{F}{L}$$

F = frictional resistance to motion in the plane of interface.

L = load perpendicular to the interface.

b. Skid Number (SN)

$$SN = 100(\mu) = 100(\frac{F}{L})$$

F = measured friction obtained with a locked-wheel standardized tire at a constant speed (usually 40 mph) along an artificially wetted pavement (in accordance with ASTM E-274 or AASHTO T-242).

L = vertical load on a locked wheel.

c. Friction Number (FN)

FN = defined by NCHRP Report 37 as the critical coefficient of friction which the tire develops before skidding occurs.

Note: It is often used interchangeably with SN in other literature to represent the measured value of skid resistance.

It is important to note that a pavement is not given a certain coefficient of friction because friction involves two bodies, the pavement and the tire. Each is extremely variable because of factors such as pavement wetness and vehicle speed. (1)

THE SKID ENVIRONMENT AND WET WEATHER ACCIDENTS

As already stated, the factors that contribute to highway skidding accidents fall into three major categories, known as the three components of skidding accidents:

- The Driver — driving habits and capabilities
- The Pavement — surface characteristics
- The Vehicle — tires and suspension

The external environment, mainly wet weather, can affect each of these components either directly or indirectly. For instance, rainfall affects the friction available from the pavement surface; the tire tread affects the capacity of the tire to remove water at the tire-pavement

interface; and wet roads can produce headlight reflection and spray, which can reduce the driver's perceptual vision and sight distance. Wet conditions produce low and variable friction values. Under dry conditions, skid resistance is good and uniform values are obtained for a wide range of surfaces. Therefore, pavement engineers concentrate their efforts regarding skidding accidents to wet conditions.

The occurrence or avoidance of a skidding accident is a function of the three interrelated components. A deficiency in any one of these components, that is, the driver, the pavement, or the vehicle, can be the cause of a skidding accident. (1)

Pavement engineers strive to understand the factors involved in skid resistance and their interrelationships. This is an extremely complex subject, and, therefore, is often outlined in terms of friction demand and supply.

Friction Demand Versus Friction Supply

Skid resistance can be thought of in terms of the margin of safety between the friction supply available and the friction demand generated at any particular time and for a particular driving maneuver. The basic skid resistance equation is as follows: skid resistance equals friction supply minus friction demand. Table 1 lists the major factors that affect the skid equation.

Table 1. The Factors of Skid Resistance (from Byrd, et al. [1])

FRICTION DEMAND	FRICTION SUPPLY
• Speed	• Speed
• Acceleration and braking	• Tire
• Vehicle characteristics	• Pavement surface Microtexture Macrotexture Drainage Cross slope
• Weather related Wind Spray Sight	• Weather related Rainfall Temperature Cyclic Effects Seasonal
• Roadway geometrics Curvature Superelevation Tracking	

Note that certain factors affect both demand and supply and can therefore have a significant influence on skid resistance. Obvious examples are speed and weather related factors. (1)

Friction Demands of Traffic

For a vehicle to follow a desired course the tires must be capable of developing definite friction factors. Friction factors vary with speed, tire type, weather conditions, roadway geometrics and, most importantly, with the maneuvers that drivers impose on their vehicles (changes in direction and rate of acceleration).

The large dependence of available friction on speed arises from the fact that on wet pavements the tire-pavement contact area is determined by the efficiency with which the tire can expel water from that area. Water viscosity and other effects cause this efficiency to degrade at higher speeds—consequently, the tire is unable to maintain a dry contact area. (1)

Friction Supply Available

Whether enough friction is produced in the tire-pavement interface under certain conditions, for example, high speed, depends on the properties of the tire, the pavement surface, and weather related factors.

The two principle factors responsible for rubber tire friction are adhesion and hysteresis; a high level of each is desirable for skid resistance. Adhesion is the product of interface shear strength and contact area. Hysteresis is caused by damping losses within the rubber when it is "flowing" over and around the mineral particle. Both are illustrated in Figure 3. (1)

The two principle factors responsible for pavement surface friction are microtexture and macrotexture; both are needed to provide the pavement surface with an adequate level of friction. The microtexture, provided by the small surface asperities, affects the level of friction in the tire-pavement contact area. The macrotexture, provided by the larger surface asperities, provides escape channels for the surface water from the tire-pavement contact area. Microtexture varies from harsh to polished, and macrotexture varies from rough to polished, as shown in Figure 4. A high drainage potential is also desirable for the pavement surface, as it allows water to escape by

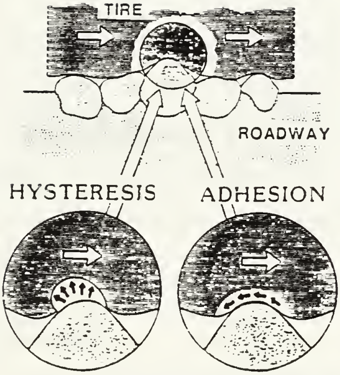

Figure 3. Rubber Tire Friction (Byrd et. al [1])

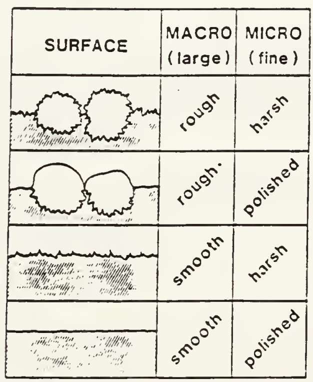

Figure 4. Pavement Surface Friction, Scale of Texture (Byrd et al. [1])

gravity; this potential reduces the water film thickness at the interface and increases available friction. (1)

Weather related factors are key to the amount of available friction. Again, in dry conditions friction is generally not a concern. Available friction is known to vary with season. Normally, available friction is relatively low in summer and fall because of contamination (oil and dirt) buildup in pavement asperities; it is relatively high in winter and spring because rainfall cleans the contamination from the asperities. (1) A drop in available friction often occurs when it rains following a period of dry days.

VARIABILITY OF SKID RESISTANCE

Identifying the major factors of skid resistance highlights an important point—a significant number of wet weather accidents are related to factors other than a slick pavement. Because of the number of contributing factors, wet-pavement skid resistance is said to have a large degree of variability. (1)

Wet-pavement skid resistance is a major concern of highway departments. However, it is a relatively small factor in relation to all accidents:

> Reported studies have indicated that most accidents, perhaps more than 80 percent, may be attributed to human factors, and only 3 to 5 percent may be attributed to vehicular characteristics or failures, with the exception of tire condition. The remaining 10 to 15 percent of accidents may be related to the roadway and its environment. (3)

To prevent skidding accidents, most states have initiated skid resistance programs that include means of measuring wet-pavement skid resistance.

SKID RESISTANCE TESTING

Skid-Testing Methodology

Since the origin of testing in the 1930s, two major methods of skid-testing have developed around the world. Although a number of devices are available for performing the tests, common methods measure either the braking-force coefficient (BFC) or the sideways-force

coefficient (SFC). The United States uses the braking-force coefficient method, whereas Europe and many other parts of the world use the sideways-force coefficient method.

The BFC is a calculation of the braking force divided by the vertical force, measured when the vehicle is braking in a straight line and the tire is actually skidding. The SFC describes the sideways force divided by the vertical force, measured when the vehicle is braking in a turn and the tire is actually skidding. Measured BFC values are usually somewhat lower than SFC values.

Skid-Testing Abroad

In Europe and other parts of the world, the skid resistance is measured by a machine appropriately referred to as the Sideways-Force Coefficient Routine Investigation Machine (SCRIM). SCRIM is based on the contention that the critical maneuver related to skidding is cornering. The test wheel is set at a 20-degree angle in relation to the direction of travel, and the sideways force acting normally to the plane of the wheel is measured. The sideways-force coefficient is then defined as the ratio of the sideways force to the vertical load. The vehicle uses a smooth tire in its measurements. The test wheel has its own deadweight, spring, and shock absorber to give a known static reaction between the tire and road. In the hub is an electrical load cell to provide the sideways-force input to the recording system. A speed input is provided from the vehicle transmission system. (1)

Skid-Testing in the United States

Skid-testing in the United States is almost universally conducted in accordance with ASTM Method E-274 (AASHTO T-242). This method uses a locked-wheel braking mechanism to measure the braking-force coefficient. The measurement represents a steady state friction force on a locked test wheel as the tire is dragged over a wetted pavement surface under constant speed. The locked test wheel's major plane is parallel to its direction of motion and perpendicular to the pavement.

The vast majority of skid measurement systems consist of a towing vehicle and a two-wheel trailer. Most commonly, the left wheel is locked during testing. The skid measurement

system must have the following: (a) a transducer associated with each test wheel that senses the force developed between the sliding wheel and the pavement during testing, (b) electronic signal conditioning equipment to receive the transducer output signal and modify it as required, and (c) suitable analog and/or digital readout equipment to record either the magnitude of the developed force or the calculated value of the resulting Skid Number (SN).

The system must include a means to transport a supply of water — usually 200 to 500 gallons — and the necessary apparatus to deliver approximately 4 gallons of water per minute, per wetted inch of pavement at 40 mph within specified limits in front of the test wheel. The system must be able to measure the speed at which the test is conducted.

A standard tire is used in the test so that the skid resistance of different pavements can be compared. The standardized skid-test tire, a tubeless, bias-ply G78x15 tire with seven circumferential grooves, is defined by ASTM E-501 (AASHTO M-261). The standard rigidly prescribes the rubber composition. Thus, the tire type and design are eliminated as variables in the measurement of pavement skid resistance.

To take a measurement, the trailer is towed at a speed of 40 mph over the dry pavement, while water is applied in front of the test wheel. The test wheel is then locked up by a suitable brake. After the test wheel has been sliding on the pavement for a certain distance, the force that the friction in the tire contact patch produces and transmits as torque on the test wheel is measured and recorded for a specified length of time. The result of such a test is reported as the Skid Number (SN).

It is essential that operators adhere to this standardized procedure. Although measurements are essentially fixed, as far as skid resistance is concerned, surface characteristics change with time and are frequently far from uniform. Unless the test is repeated and measurements made in an identical manner, the operators may conclude that changes occurred when they really did not and distort the magnitude of real changes. (1)

The possibility of some uncertainty in the measurements remains. Seasonal variations exist, as shown by several studies. In addition, temperature effects exist because of tire friction's

dependence on temperature. Operators must also consider a complicated interplay that involves air, pavement, and water temperatures, as well as the heating of the tire structure by flexing and the heating of the tire tread by friction. (1) No universally accepted method of correcting skid number for temperature exists yet; however, researchers are finding that the effect of reasonable air temperatures (25°F-70°F) on pavement surface friction is insignificant.

There are other potential sources of error. Some sources affect the repeatability of a test made with the same tester, while others cause different testers to produce different results on the same surface under the same conditions. A potentially large source of error is position of the wheel in the wheelpath.

However, these imperfections do not diminish the usefulness of ASTM E-274 for most purposes, such as (a) determining whether pavement friction could be a governing factor at highway accident locations, (b) making surveys of a road system for the purpose of identifying low friction sections and setting priorities for remedial programs, and (c) determining the relative in-service skid number of different types of construction, aggregates, and surface treatments. Difficulties arise only when high precision is needed, as when engineers must determine whether a particular surface meets a mandated level of skid resistance. (1)

DETECTION OF SLIPPERY CONDITIONS BY SKID-TESTING

Skid-testing may be performed for a wide variety of reasons; however, the primary reason is to detect low friction pavements that may be corrected to prevent accidents. For researchers to use the skid-test equipment to detect slippery pavement conditions, the term "slippery" must be translated into skid numbers. For skid-testing to be used as an effective tool, decisions have to be made, at least within a transportation department, as to acceptable or reasonable skid numbers. This decision making becomes further complicated when variation in friction demand is taken into consideration, as discussed in a previous section. (1)

Many states have developed their own ranges of skid resistance values. The ranges may vary by classification of road, by traffic volume, or by any other valid reason. Many other states

use the skid values from NCHRP Report 37 (1967), which recommends a minimum skid number of 37 for highways. (1)

CALIBRATION AND CORRELATION

As with any other measurement, skid resistance measurements are of limited value, or may even be totally useless, unless the measuring system obtains data that fall within acceptable limits of accuracy and precision. Accuracy refers to the measurement's degree of agreement with an accepted reference level. Precision refers to the degree of agreement among repeat measurements. To ensure accuracy and precision the system must be calibrated periodically.

Because skid resistance is a performance measure, that is, the force required to drag a specified tire over a wetted pavement under specified conditions, no absolute standard exists to which the measured values may be compared or related. To address this problem, correlation studies were conducted in which the results, obtained with different skid resistance testers, were compared with each other. These correlation studies resulted in significant improvements in the accuracy and precision of skid resistance measurements.

However, the correlation studies did not solve the problem. When different skid-testers were correlated, the mean of the results of all testers was used as a reference level. This method proved to be unsatisfactory because in all correlation studies the difference among the measurements of several testers, under presumably identical conditions, was found to be statistically significant. This meant that systematic errors were much larger than random ones. The method of applying the water in front of the test tire is an example of a systematic error, while placement in the wheel track is an example of a random error.

NCHRP Report 151 (13) summarized the factors in skid resistance measurement in terms of the type and magnitude of error that each factor introduces. The summary is provided in Appendix A. Report 151, in conjunction with more recent findings on error, has been used to upgrade ASTM E-274; in particular the report specified the limits within which tester components and instruments must perform. These limits are compromises between what is

permissible and what is practical. Every operator must periodically calibrate the tester to assure that it conforms to the requirements of ASTM E-274. (1)

Field Test and Evaluation Centers

To aid users of skid resistance testers and to assure that reported skid numbers were related to a common basis, Field Test and Evaluation Centers (FT & EC) were established at the Texas Transportation Institute (College Station, Texas) and Ohio State University (East Liberty, Ohio). At the centers, skid-testers are dynamically calibrated, correlated, and evaluated while operating personnel are instructed on proper test procedures.

Researchers at the centers calibrate a user's tester against a standard tester. The standard tester is in turn calibrated against a primary reference tester maintained by the National Bureau of Standards.

"Standard surfaces" are used for the calibration runs, which span the range of skid resistance values that are typically encountered in fieldwork. The surfaces are subjected to use and weather skid resistance variations similar to those experienced by highway pavements. Because the surfaces are subjected to such conditions, researchers cannot calibrate a tester directly on them by running a series of skid-tests and making appropriate adjustments until the mean of the measured values agrees with the skid resistance of the standard test surfaces. Instead, correlation tests with the secondary tester are made. (1)

Calibration Procedures

There is no way to predict how long a tester will stay calibrated. For practical and economic reasons a tester may be taken to a field test and evaluation center only occasionally; tester checks are recommended once every two years. Hence, the user must recalibrate and maintain the tester between visits to a national center. As a minimum, the following items require attention:

- Speed Measurement — The skid resistance of common pavements is a strong function of speed. It is therefore essential that test speeds are accurately measured.

- Water Application — The water application process involves the proper functioning of the water nozzle and its correct positioning. In addition, the discharge rate of the nozzle must be within specifications.

- Wheel Load — As long as no changes have been made on the trailer, the wheel load may be assumed to be unchanged.

- Skid Resistance — A static calibration of the wheel force is performed to simulate the traction force between the tire and the pavement. The calibration system consists of a calibration platform, a horizontal drive mechanism, and a force transducer. The calibration platform consists of a bearing that is frictionless in all directions of the horizontal plane; the horizontal plane supports a rigid plate with a high friction surface. With the test wheel placed on the calibration platform, a tractive force is applied to the platform by a horizontal drive mechanism (see Figure 5). The applied force is measured by a force transducer and compared to the test wheel transducer output. The force is applied in 100 lbf increments up to 80 percent of the wheel load or until the plate starts to slip under the tire, whichever occurs first. At each increment, the indicators of the platform transducer and the test wheel transducer are allowed to come to rest and force readings are recorded. The recommended accuracy is 1 percent or better. Mechanical or electronic adjustments are made until the force readings are equal. Alternatively, calibration curves or tables may be prepared to be used as corrections to measured results. This calibration procedure is performed in accordance with ASTM Method E-556 (AASHTO Method T-282) and ASTM Method F-377. (29, 30)

- Test Tires — Although test tires in the past have shown remarkable uniformity, this uniformity cannot be assumed to be true—especially if a tire has been stored or has seen considerable use. The break-in and conditioning procedures prescribed by ASTM E-501 should be followed meticulously. Because inflation pressure is an important variable, it should be measured with a calibrated gauge.

- General — All components and functions that have any effect on the validity of the measured skid resistance values should be checked and corrected as needed. This may include the cycle timer, brake system performance, and wheel balance. (1)

Operating Procedures

Operating and data evaluation procedures must also conform to certain limits and standards. The ASTM E-274 method provides some guidance in performing these procedures; however, to a large extent, operator performance is a matter of skill, experience, and an understanding of the skid resistance measuring process. (1)

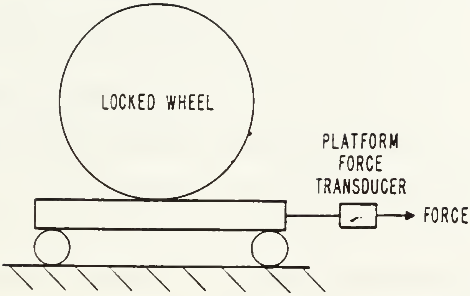

Figure 5. Calibration of Locked Wheel (ASTM [30])

CHAPTER 2

LITERATURE SEARCH

A literature search was conducted for research reports pertinent to this paper and for written guidelines on the WSDOT's skid resistance program. Although a substantial amount of literature was available on pavement skid resistance, only a portion of it was useful for the examination of minimum skid resistance guidelines.

THE WSDOT SKID-TESTING PROGRAM

The current WSDOT guideline for skid resistance is based, in part, on NCHRP Report 37, which designates SN = 37 as the recommended minimum skid number (tentative and interim) for highways. The WSDOT guideline agrees with a 1986 report by Wambolt, et al. that states, "Based on the experience from many states, it is generally agreed that a skid number of 35 or greater gives adequate skid resistance under most conditions." (21)

The WSDOT skid-testing program meets the national standards (ASTM) for testing and calibration. The WSDOT skid-test equipment, calibration, and data storage techniques are discussed in this section. In addition, the FN inventory and its role in the WSDOT Pavement Management System database are addressed.

WSDOT has been involved in pavement friction testing with locked-wheel equipment since 1968. The WSDOT Materials Laboratory, Special Projects Section, is responsible for the skid-testing program. The intent of the program is to point out those areas that have a potential problem regarding skidding accidents. WSDOT operates one Cox & Sons Model CS 9000 Locked-Wheel Skid-Tester, in accordance with ASTM Method E-274(80), and uses a ribbed test tire, in accordance with ASTM E-501. (25) A picture of the WSDOT skid measurement system is provided in Figure 6, an interior view in Figure 7, and a nozzle view in Figure 8. (21) The WSDOT is due to receive a new test trailer in late 1993. The new trailer will meet ASTM E-274(90) and will introduce many improvements, including more accurate calibration.

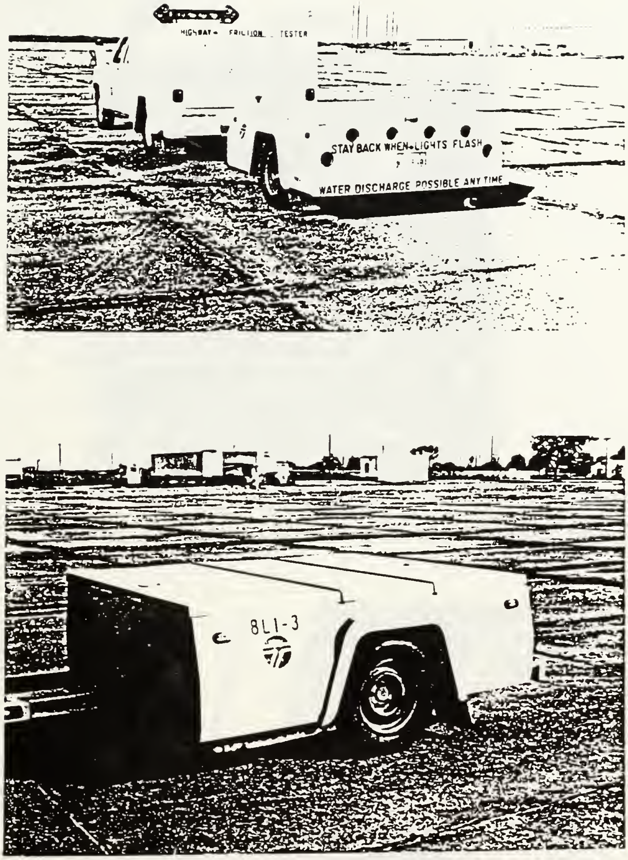

Figure 6. Washington No. 3 SMS (Texas Transportation Institute [20])

Figure 7. Interior View of Washington No.3 (Texas Transportation Institute [20])

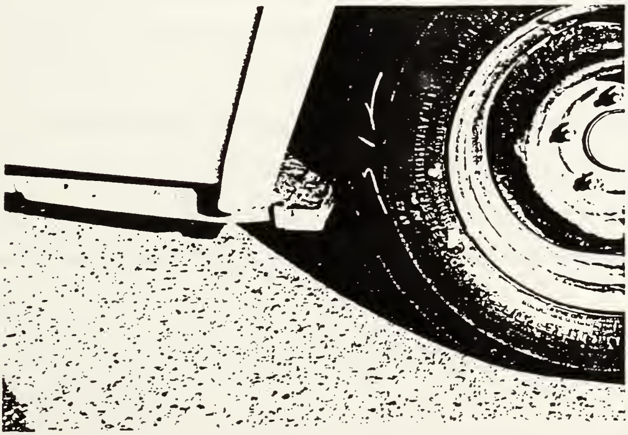

Figure 8. Nozzle View of Washington No. 3 (Texas Transportation Institute [20])

The Washington State highway system comprises 7,000 centerline miles. (24) The entire system is tested every 2 years. The highway system is divided into six districts; each year the highways in three of the six districts are tested for skid resistance. Districts 1, 3, and 5 are tested during even-numbered years, and Districts 2, 4, and 6 are tested during odd-numbered years. The pavement in the left wheel track of the slow lane is tested and recorded at each milepost, in each direction on multilane highways and one direction on two lane highways. The length of the test is 117 ft and takes 2 seconds at the standard test speed of 40 mph. (27) Skid resistance generally does not change drastically over a 1-mile section of highway; therefore, this is a viable method for testing the whole road network.

Newly paved sections of highway are friction tested as soon as possible after completion. All lanes are tested in both directions, with a minimum of eight tests per project. (26)

The friction number is recorded at each milepost. The skid-tester generates a computer output of the measured friction numbers. The results are tabulated by highway, milepost to the 0.01 of a mile, direction of travel, lane, surface type, and speed. The skid numbers are corrected to a national standard for friction measurements, to which the WSDOT skid-tester has been calibrated. If the test speed was other than 40 mph, the tests are also corrected to a friction number at 40 mph. (27) This output is combined into a yearly pavement friction inventory. The district managers receive their portion of the inventory and are advised to take action on those roads that have a recorded friction number of less than 35. This guideline to report pavement friction numbers of less than 35 accompanies the inventory in the form of a memorandum to the district managers, as shown in Appendix B. (26) The friction numbers are also entered into the WSDOT Pavement Management System, which compiles data for each milepost in the state highway system.

For continuity of the test results, no testing is performed during freezing weather conditions or during heavy rainfall.

The WSDOT skid-testing equipment is calibrated once every 2 years at the Texas Transportation Institute. In the interim, the equipment is calibrated both statically and

dynamically by WSDOT personnel. Because skid-testers operate at relatively high speeds, the ultimate calibration is a "dynamic" test conducted on a surface of known and near constant friction properties. The WSDOT skid trailer undergoes this dynamic test an average of once a month at three specified pavement sections near the WSDOT Materials Laboratory in Olympia, Washington. Two of the dynamic test sites are asphalt concrete pavements (ACP), SR101 MP 365.00 and SR5 MP 92.00. The third site, SR5 MP 111.00, is a portland cement concrete pavement (PCCP). At each site 10 tests are run at intervals of 0.10 mile for 1 mile. The results are generated and later plotted, as shown in Appendix C. After each testing cycle, the results are compared to previous cycle results for the corresponding pavement in order to ensure the skid-test equipment is operating consistently during similar environmental conditions. Precipitation data from the Olympia weather station are also plotted and used along with the friction number data to evaluate tester performance. The next best alternative to the dynamic test is a "static" test, which WSDOT also performs once per month. This "static" test is usually performed on the same day as the dynamic test. The WSDOT follows the standard procedures for conducting the static tests (see Calibration Procedures section, Chapter 1, for details).

UNITED STATES LITERATURE

Federal Guidelines

The primary sources for the national position on skid resistance guidelines are the National Cooperative Highway Research Program (NCHRP) Reports. The NCHRP Report 37 (1967) set SN = 37 as the minimum, tentative, and interim skid resistance requirement for the national road network. (12) The NCHRP Report 151 (1974) investigated locked-wheel pavement skid-tester correlation and calibration techniques and acceptable windows of error. (13) The NCHRP Report 154 (1974) set tentative minimum skid resistance requirements at intersections. (4)

Federal and State Research

The NCHRP Synthesis of Highway Practice 14 (1972) assembled information on skid resistance from many highway departments and agencies. (9) The NCHRP Synthesis of

Highway Practice 158 (1990) surveyed highway departments throughout the U.S. and provided information regarding their wet-pavement safety programs. (3)

Federal and state sponsored research reports were essential for analyzing the interim skid resistance requirements recommended in 1967 and for the proposal of new guidelines. Research studies sponsored by Maryland, Pennsylvania, California, and Illinois are referenced in this report. These studies further supported (a) the conclusion that skid numbers can only be used as a guideline and not as a rigid requirement because of the number and variability of factors involved, (b) specific conclusions regarding areas of pavement temperature and skid-tester correlation/calibration, and (c) ideas for the format and range of the proposed skid resistance guidelines. The Maryland and Pennsylvania reports are discussed in great detail later in the Methodology and Results section.

The California Department of Transportation (CALTRANS) report studied wet accident rates and found that

> Curves have the highest accident rate followed by weave sections and intersections. As one would expect, these rates are substantially higher at locations having skid numbers less than 25. The accident rate is nearly constant on pavements with skid numbers greater than 26, but it increases substantially as the skid numbers decrease from 25 to 17. (18)

Furthermore, the report stated,

> Nationwide, several studies have been completed in an attempt to establish criteria that would minimize wet-pavement accidents by establishing minimum skid numbers. In the past, when a minimum value has been proposed by another agency, an in-house investigation by CALTRANS Traffic Engineers has shown that many locations have skid numbers less than the proposed value with no record of a wet-pavement accident problem. Therefore, it has been considered inappropriate to adopt minimum skid number levels because of the difficulty in establishing justifiable values and because the adoption of a value higher than necessary would require utilization of limited highway improvement funds that should be used to improve known problem areas. (18)

The Illinois Department of Transportation guidelines were more conservative than CALTRANS, but still set friction guidelines significantly lower than those recommended in NCHRP Report 37. The Illinois tentative guidelines for evaluating friction at high wet accident sites after 1987 included the following:

(a) if the FN is less than or equal to 30, friction is probably a factor contributing to wet-pavement accidents,

(b) if the FN is greater than 31 but less than 35, uncertainty exists as to whether pavement friction is the primary factor, and

(c) if the FN is greater than or equal to 36, some condition other than pavement friction is probably the primary factor causing wet-pavement accidents. (6)

Practically every state has a skid-testing program. Each program was summarized in NCHRP Synthesis of Highway Practice 158 (1991). The states were asked to report their criteria for evaluating skid-tests; state answers ranged from NCHRP Report 37's recommended minimum skid number of 37 to a variety of acceptable, marginal, and unacceptable skid numbers. The state guidelines similar to those recommended in this paper are provided in Table 2. (3)

Most of the recent literature on skid-testing encouraged highway departments to use the smooth tire procedure (ASTM E-524 or AASHTO M-286) for routine measurement. The literature suggested that if only one tire is to be used, it ought to be the smooth tire; this is because the smooth tire is equally sensitive to micro- and macro-texture, whereas the ribbed tire responds primarily to the microtexture. Furthermore, early attempts to relate accident data to skid resistance measured with a ribbed tire were frustrating. Figure 9 shows that there is a minimal correlation between the measure of wet-pavement safety and the skid number when measurements are made with the ribbed tire. Figure 10 compares the measured skid number with a ribbed tire (SN_{40R}) to that of a smooth tire (SN_{40S}). One notices that the level on the vertical axis that separates most of the high wet accident rate sites from the low wet accident rate sites is 25. On the other hand, no obvious value on the horizontal axis separates the high- and low-accident sites. This absence of a value results in an "unclear" level of SN_{40R} that separates the high- and low-accident sites. (8)

INTERNATIONAL LITERATURE

The international arena, particularly Great Britain and Italy, provide a comparison of skid resistance ranges. The standard in Italy for minimum highway skid resistance is surprisingly similar to the results in this report. The Great Britain standard, on the other hand, is somewhat

Table 2. Summary of Friction Guidelines for State Highway Departments (Guidelines Similar to This Paper's Recommendation) (Dahir, et al. [3], updated by Ref. [6] for Illinois)

STATE	CRITERIA TO EVALUATE TESTS	THRESHOLDS AND ACTIONS
California	Office of traffic safety notified when SN40 is below 30.	Varies
Idaho	Change or range in numbers.	At 35 section is listed. At 30 section is recommendable.
Illinois	Less than FN40 = 35.	• FN ≤ 30 — friction is probably a factor contributing to wet-pavement accidents. • 31 ≤ FN ≤ 35 — uncertainty exists as to whether pavement friction is the primary factor, and • FN ≥ 36 — some condition other than pavement friction is probably the primary factor causing wet pavement accidents.
Indiana	Trends from past data and 30 as a minimum friction number.	FN40 = 30
Louisiana	SN equal to or over 35 for new construction.	Not clearly established (below SN 30 with high ADT).
Michigan	Comparison with past results.	Special attention given to investigate surfaces with SN at 30 or below.
Ohio	Below 30 - poor: 30 to 40 - adequate, depending on traffic and geometry over 40 - satisfactory	Some type of correction likely where SN = 30.
South Dakota	Action taken below FN 31.	Action taken below FN 31.
Tennessee	Above FN 35 - acceptable: FN 30 to 35 - questionable: below 30 - unsatisfactory.	Above FN 35 - acceptable: FN 30 to 35 - questionable: below 30 - unsatisfactory.
Vermont	Monitor area if SN is 40 or below; inform proper personnel of problem when SN is below 30.	
Virginia	Based on bald tire FN40 minimum of approximately 20.	

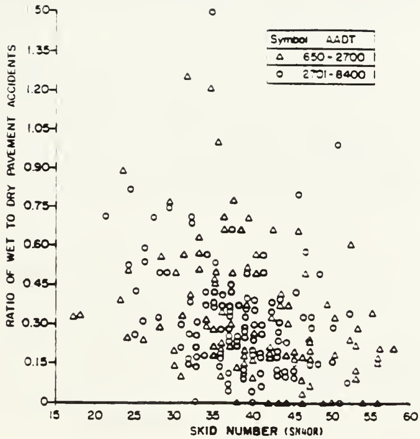

Figure 9. Ratio of Wet-to-Dry Pavement Accidents Versus Skid Number for a 3-Year Period in Kentucky (AADT = Annual Average Daily Traffic) (Henry and Wambold [9])

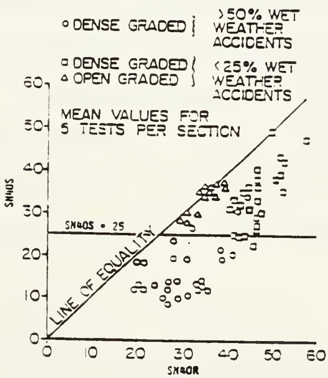

Figure 10. Skid Numbers SN40R (ribbed tire) and SN40S (smooth tire) Measured at Accident Sites in Florida: Mean Values for Five Tests per Section (Henry and Wambold [9])

higher. In order to compare a SCRIM measurement to a U.S. locked-wheel trailer measurement. the SCRIM measurement must be converted from a sideways-force coefficient to a braking-force coefficient. Typically,

$$BFC = SFC \times 0.80 \quad (\underline{10})$$

It is also important to note that SCRIM measures SFC at 50 km/hr (30 mph). (10) To convert this value to an SN at 40 mph, using gradient = 0.2 SN/mph. the calculation is as follows:

$$SN = (BFC \times 100) + 0.2\ SN/mph\ (30\text{-}40)$$

$$SN = (BFC \times 100)\ \text{-}2\ SN$$

In Italy a pavement is considered slippery when SFC is less than 0.30 on highways. (2) Comparing this value to a U.S. measured SN:

$$SN = (SFC \times 0.8 \times 100) - 2$$

$$SN = (0.3 \times 0.8 \times 100) - 2$$

$$SN = 22$$

This SN is much lower than the U.S. guideline (recommended in 1967) of SN = 37.

The Great Britain skid resistance policy sets investigatory levels of Mean Summer SCRIM Coefficient (MSSC) at 13 different site categories, which are thought to cover the whole trunk-road network, as shown in Appendix D. This new policy was introduced in 1988 by England's Minister for Roads and Traffic. It is important to note that the Great Britain policy is stated in terms of MSSC, which is the friction ratio (SFC) multiplied by a factor of 0.78, as follows:

$$MSSC = SFC \times 0.78 \qquad (\underline{5})$$

To compare the MSSC values in Appendix E to SN values, the equation is amended as follows:

$$BFC = SFC \times 0.80$$

$$BFC = \frac{MSSC}{0.78} \times 0.80$$

$$BFC = MSSC \times 1.026$$

To convert this to an SN at 40 mph, using gradient = 0.2 SN/mph, the calculation is as follows:

$$SN = (BFC \times 100) - 2\ SN$$

$$SN = (MSSC \times 1.026 \times 100) - 2\ SN$$

The table in Appendix E shows that the Great Britain standard for a Motorway (Mainline) is MSSC = 0.35. To compare this value to a United States measured SN one must compute the following:

$$SN = (0.35 \times 1.026 \times 100) - 2$$

$$SN = 34$$

This SN is lower than the United States guideline of SN = 37 for main rural highways.

This examination of current standards abroad raises the question of whether the NCHRP guidelines for highways is too conservative; this paper investigates that question.

CHAPTER 3

METHODOLOGY AND RESULTS

FRICTION GUIDELINES FOR MAIN RURAL HIGHWAYS

It is important to recognize that the skid resistance value of SN = 37 recommended in NCHRP Report 37 is not a standard and is based on 1967 knowledge. Various jurisdictions have adopted or prescribed minimum skid resistance values based on their own considerations. These considerations have included intuition and experience. Sometimes jurisdictions have included provisions for higher SN values at specified locations. (3)

In their report (NCHRP Report 37), Kummer and Meyer developed the minimum skid resistance requirements by establishing friction factors based on traffic needs. They then tackled the problem of defining minimum skid resistance requirements. The next section provides a detailed review of their methodology, followed by an application of up-to-date changes to determine the effect of temperature and calibration accuracy on skid resistance values. The purpose of updating the skid resistance guideline is to prevent the use of an excessively high minimum SN. An artificially high SN increases the total cost of skid-proofing a highway system without providing a significant benefit to traffic and accident prevention. The NCHRP Report 37 states, "In the author's view excessive minimum skid resistance requirements are self-defeating." (12)

THE 1967 RECOMMENDED MINIMUM SKID NUMBER

The NCHRP Report 37 showed that a friction number of 40 satisfied the normal frictional needs of traffic on main rural highways, and, hence, on any road that carried traffic at lower speeds. Skidding accident studies and a comparison of driver deceleration patterns during braking and cornering proved that a friction number of 40 satisfied the frictional needs of all normal vehicle maneuvers during acceleration, driving, cornering, and deceleration.

Furthermore, the studies showed that a friction number of 40 did this over a wide speed range (except toward the end of braking maneuvers that lead to a full stop).

Under ideal conditions—that is, in the absence of other friction components (laterally during acceleration and braking, and fore and aft during cornering) and wheel load fluctuations (caused either by tire runout, wheel imbalance, or pavement irregularities)—a friction number of 40 would satisfy the normal frictional needs of traffic. However, in actual conditions, a higher friction number is needed to account for other friction components and wheel load fluctuations that are present in all driving.

• To convert friction numbers that satisfy the normal needs of traffic into skid numbers, Kummer and Meyer made reasonable allowances for the following:

a. other friction components ,
b. wheel load fluctuations,
c. K-factors,
d. wet pavement temperature, and
e. machine error of present skid trailers.

Accordingly, they had five steps in the conversion process. Each step was broken down into lines, as summarized in Table 3 and Figure 11. These steps are examined for opportunities to adjust variables and thus produce a new skid number. It is helpful to follow Table 3 as the steps are reviewed.

Step 1

The minimum required resultant friction number, $\overline{FN}$, is determined. The $\overline{FN}$ assures the availability of friction for the principal vehicle maneuver under ideal conditions (FN_0), and also allows for an additional friction component in the fore and aft or the lateral direction.

Line 1: $FN_0 = 40$ is the minimum friction number for the speed range 40 mph to 80 mph; this number was established by a driver behavior study. The FN_0 increases linearly to $FN_0 = 50$ at 0 mph because of the higher decelerations required at the end of a stop.

Table 3. Conversion of Friction Numbers that Satisfy the Normal Need of Traffic into Skid Numbers (Kummer and Meyer [12])

	LINE	CONVERSION STEPS	SKID NUMBER FOR MEAN TRAFFIC SPEED, V, OF 0 MPH	10 MPH	20 MPH	30 MPH	40 MPH	50 MPH	60 MPH	70 MPH	80 MPH
STEP 1	1	FN_0	50	47.5	45	42.5	40	40	40	40	40
	2	CSN	—	—	1.6	3.6	6.4	10.0	14.4	19.6	25.5
STEP 2	3	$\overline{FN}$	50	47.5	45	42.7	40.4	41.1	42.4	44.5	47.0
	4	$\Delta L/L$(%)	—	—	2.5	5.0	7.5	10.0	12.5	15.0	18.5
	5	FN_d	50	47.5	46.1	44.8	43.5	45.0	47.7	51.2	55.2
STEP 3	6	K-factor	1	1.3	1.6	1.8	2.0	2.2	2.4	2.6	2.8
	7	SN_0	50	37.5	28.8	25	21.8	20.5	20	19.7	19.8
STEP 4	8	SN_t	56	43.5	34.8	31	27.8	26.5	26	25.7	25.8
STEP 5	9	SN	61	48.5	39.8	36	32.8	31.5	31	30.7	30.8
	10	SN(rounded)	60	50	40	35	33	32	31	31	31

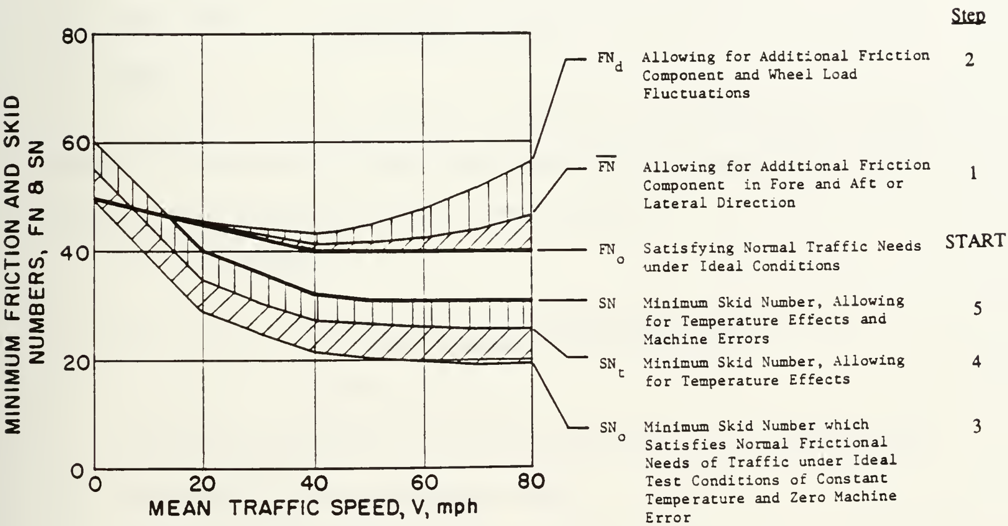

Figure 11. Conversion of Normal Frictional Needs of Traffic into Skid Numbers (Kummer and Meyer [12])

Line 2: $CSN = C \times V^2$

where CSN = cornering slip number,

C = steering correction constant $= \frac{1}{250}$, and

V = speed.

The cornering slip number (CSN) factor is applied to account for the lateral friction component due to steering corrections made by the driver. The corrections are deviations from the driver's intended path and may be caused by road crown, inattention, and cross winds, to name a few. The researchers measured the vehicle's lateral decelerations that resulted from driving and braking on a straight course. A cornering slip number of up to 10 at 50 mph, which increases to a maximum of 20 at 70 mph, was also measured.

Line 3: $\overline{FN} = \sqrt{(FN_0)^2 + (CSN)^2}$

where $\overline{FN}$ = resultant friction number.

Step 2

The dynamic friction number, FN_d, is calculated to compensate for the temporary reduction of the wheel load by ΔL during braking or cornering; it correspondingly increases the friction number to prevent either wheel lock or lateral breakaway.

Line 4: $\frac{\Delta L}{L}$ (percent)

where ΔL = the increase or reduction of average wheel load because of tire run-out, wheel imbalance, or pavement roughness.

L = the average wheel load.

The $\frac{\Delta L}{L}$ value was estimated by measuring the dynamic wheel loads of passenger cars on selected pavement surfaces and at different speeds.

Line 5: $FN_d = \left[\frac{1}{\left(1 \pm \frac{\Delta L}{L}\right)}\right] \times \overline{FN}$

where FN_d = the dynamic friction number, which allows for additional friction components, and wheel load fluctuations.

Step 3

To convert the dynamic friction number, FN_d, into a corresponding skid number, SN_o, a K-factor is used. The K-factor accounts for the fact that vehicles "see" transient critical friction numbers before skidding occurs, whereas pavement skid resistance is measured under quasi-steady-state conditions. These critical friction numbers are higher than skid tester obtained skid numbers, which, in part, are due to lower tire temperatures during testing (thus higher friction levels). Thus, the K-factor, which accounts for typically used tread designs, rubber compositions, and surface types, is used to convert the needed pavement friction to a measured pavement friction.

Line 6: $K = \frac{FN}{SN}$

where FN = the transient friction number, and

SN = the steady-state skid number.

Line 7: $SN_o = \frac{FN_d}{K}$

where SN_o = the minimum skid number that satisfies the normal frictional needs of traffic under the ideal test conditions of constant temperature and zero machine error.

The K-factors used in NCHRP Report 37 were obtained from results reported by Maycock and are shown in Table 3. (32) They are mean ratio's of BSN (Brake Skid Number—measured under transient conditions) divided by SN (Skid Number—measured under steady-state conditions).

Step 4

The SN_o is adjusted for pavement temperature effects, resulting in SN_t. In 1967 pavement temperature was thought to have a significant effect on skid number. However, it was impractical in routine skid resistance surveys to constantly monitor wet pavement temperature in order to correct the data. Therefore, the researchers developed a correction factor in the laboratory by measuring the British Pendulum Number (BPN) with natural rubber sliders on a bituminous concrete surface. The authors chose a conservative gradient of $0.3 \frac{SN}{°F}$, which was much higher than the results of other researchers at the time. This experiment suggested that

further work was needed to establish a reliable correction factor. The temperature correction factor is examined later in this report.

Line 8: $[0.3 \frac{SN}{^{\circ}F} \text{gradient}] \times 20^{\circ}F = 6$

$$SN_t = SN_0 + 6$$

where SN_t = minimum skid number, allowing for temperature effects.

To safeguard against operators overrating a surface because of low wet-pavement temperatures, 70°F is assumed to be the mean wet pavement temperature, with a maximum deviation of ±20°F. The resulting range of 50°F to 90°F should include the majority of test conditions encountered in the U.S.

Step 5

The SN_t is adjusted for skidtrailer machine errors, resulting in SN.

Line 9: $SN = SN_t + 5$

where SN = the minimum skid number, allowing for temperature effects and machine errors.

A detailed analysis made with the Penn State road friction tester revealed a measurement uncertainty that was attributable to a machine error of approximately one to two skid numbers. The authors chose five skid numbers as a conservative but typical machine error for U.S. two-wheel trailers in 1967. The calibration and correlation of skid trailers in the U.S. have improved considerably since 1967. The calibration/correlation correction factors are examined later in this report.

Line 10: The SN (rounded) is the lowest recommended skid number for the corresponding mean traffic speed, V. The mean speed of traffic the researchers were concerned with was V = 50 mph. This was established by a driver behavior study, where researchers found the speeds of most concern were between 40 and 60 mph, hence the average value of 50 mph was chosen for analysis. The SN (rounded) at 50 mph = 32.

Conversion to SN_{40}: The standard testing speed of a two-wheel trailer is 40 mph. The skid number measured at 40 mph includes an allowance for the reduced skid number and speed by using a mean gradient of G = 0.5 SN/mph, as shown in Table 4.

Table 4. Recommended Minimum Interim Skid Numbers (Kummer and Meyer [12])

Mean Traffic Speed, V (mph)	Skid Number[a]	
	SN[b]	SN_{40}[c]
0	60	—
10	50	—
20	40	—
30	36	31
40	33	33
50	32	37
60	31	41
70	31	46
80	31	51

[a] Skid numbers in accordance with ASTM E-274 Method of Test
[b] SN = skid number, measured at mean traffic speeds
[c] SN = skid number, measured at 40 mph, including allowance for the skid number reduction with speed using a mean gradient of G = 0.5

SN_{40} = the SN rounded (at V) + [0.5 SN/mph × (V - 40 mph)]

where V = the mean traffic speed

$$SN_{40} = 32 + [0.5 \text{ SN/mph} \times (50 - 40 \text{ mph})]$$
$$= 32 + 5$$
$$= 37$$

Therefore, the lowest recommended skid number in 1967 was $SN_{40} = 37$.

It is important to note that the authors of NCHRP Report 37 did not consider seasonal fluctuations of the pavement's skid resistance. Rather than adding another correction factor, for which only limited data were available, the researchers based the minimum requirements on the assumption that the skid-tests would be made in summer and fall seasons, when skid resistance is lowest. (12)

RECOMMENDED CHANGES TO THE 1967 MINIMUM SKID NUMBER

Adjustments were applied to the previously derived minimum skid number to reflect current knowledge. These adjustments specifically addressed step 4, pavement temperature effects, step 5, machine errors, and lastly, speed gradient.

Pavement Temperature Effects

Before the specific changes to step 4 are addressed, a more thorough presentation of the NCHRP Report 37 researchers' point of view must be provided. The researchers estimated the pavement temperature effect on SN on the basis of three graphs. The results of the first graph, as shown in Figure 12, emphasized the similarity of the curves of wet skidding accidents rates and mean air temperatures and suggested that increasing temperatures during the summer months causes a decrease in the pavement friction level. The results also emphasized the role of rubber tire friction, by suggesting that an increase in pavement temperature causes a reduction in the hysteresis component of tire friction and, under some conditions, a reduction in the adhesion component. (12) However, the researchers did not recognize that a more likely reason for the increase in skidding accidents during the summer was the buildup of contamination in pavement asperities, attributable to the decrease in rainfall. (The Maryland study showed that rainfall has a much more significant effect on SN than does pavement temperature, as discussed later in this section.) The second graph, shown in Figure 13, illustrates the decrease in BPN with wet surface temperature, which for this case is 0.25 BPN/°F. The authors' test resulted in a gradient of 0.20, while Britain's Transport and Road Research Laboratory (TRRL) quoted a gradient of 0.13. Therefore, the authors' estimate of 0.3 BPN/°F was very conservative. The third graph, shown in Figure 14, illustrates the results of a study by Finney and Brown, which measured the steady-state skid resistance on a bituminous concrete surface. They found a skid number reduction gradient of 0.3 SN/°F. Finney and Brown's research revealed some correlation between pavement temperature and SN, but further work needed to be done to establish a reliable correction factor.

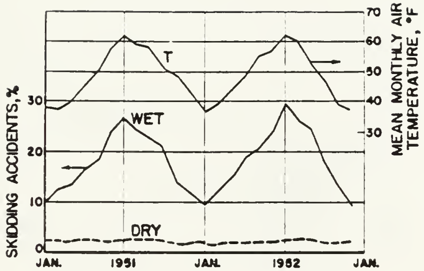

Figure 12. Seasonal Fluctuations of Skidding Accidents and Air Temperature, Suggesting a Friction-Temperature Interaction (Kummer and Meyer [12])

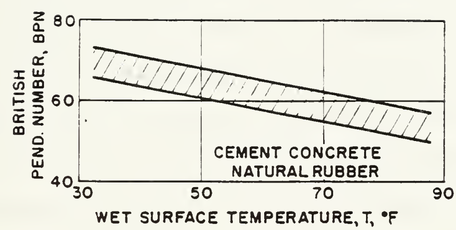

Figure 13. Reduction of British Pendulum Number due to Temperature-Originated Decrease in Rubber Damping (Kummer and Meyer [12])

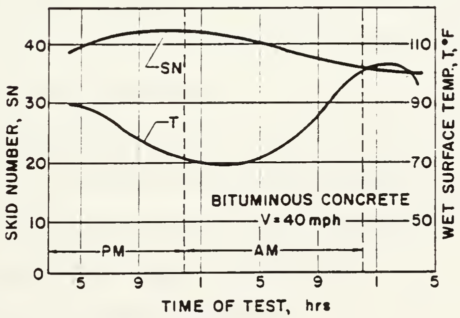

Figure 14. Influence of Hourly Changes in Wet Surface Temperatures on Steady-State Skid Number (Kummer and Meyer [12])

Recent research reveals that SN corrections for pavement temperature are not necessary. Even in 1967, researchers were not sure how much pavement temperature affected SN. The authors of NCHRP Report 37 stated, "Although it can safely be stated that the slip and skid resistance of a tire-pavement combination will, as a rule decrease with higher temperatures, it is as yet impossible to reliably predict the reduction." Consequently, the researchers made a conservative correction to the SN that was based on the knowledge they had at that time. (12)

Although it has long been recognized that skid resistance measurements exhibit short-term variations because of pavement temperature effects (skid resistance generally decreases as the temperature increases), the degree of the effects is debated. The NCHRP Report 37 suggested a SN/°F gradient of 0.3; however, more recent reports have suggested a much lower gradient, which incidentally has a negligible effect on the final skid number. In NCHRP Report 151 (1974) researchers concluded from tests that temperature effects are very small and are often overshadowed by the data spread because of other causes. Researchers also found that correction factors vary with pavement type. Furthermore, to determine temperature correction factors, a single skid-tester should be used in a large number of repeat tests. The tests should be carried out over a large temperature range and within a short period. Unless the data spread from other sources can be kept to a minimum, temperature corrections need not be considered. Specifically, the report concluded the following:

1. Temperature correction factors are small, on the order of 2 percent per 10°F (see Figure 15). In comparison to the previously mentioned gradient, which resulted in a correction of 6 SN, this gradient yields a correction of 0.04 SN, as follows:

   $$[0.02\ \text{SN}/10°\text{F gradient}] \times 20°\text{F} = 0.04\ \text{SN}$$

   This is clearly an insignificant correction.

2. Because of the slight effect of temperature on skid resistance, correction should be attempted only if both skid resistance and temperature measurements are sufficiently reliable. (13)

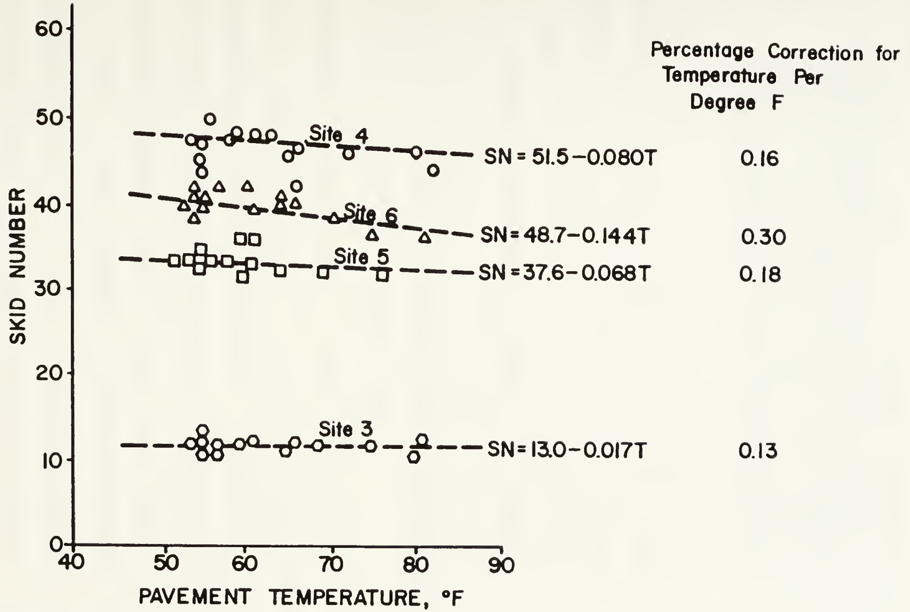

Figure 15. A Plot of Skid Numbers versus Temperatures (Meyer et al [13])

Researchers have also concluded from recent studies that pavement temperature does not appreciably affect skid resistance. The Maryland Department of Transportation sponsored a research study in 1986 to investigate seasonal variations of friction numbers. It concluded,

> Researchers are divided when it comes to conclusions relative to the effects of pavement temperature on friction numbers. Graphs of the data derived from this study [as shown in Appendix E] leave little doubt as to where Maryland will stand on this issue. As can be seen, there is no discernible relationship between the two parameters. Collaboration of this can be obtained by scrutinizing the data resulting from regression analyses [as shown in Appendix E]. Not only are the coefficients virtually zero, but the slopes of the lines show that friction numbers are not effected [sic] by the pavement temperature. (14)

Researchers agree that in both northern and southern states, short-term variations in skid resistance appear to be the result of variations in local weather conditions, specifically rainfall and temperature. In 1989, rainfall was shown to have a more pronounced effect on skid resistance than pavement temperature in a research report by the Pennsylvania Transportation Institute, in coordination with the Federal Highway Administration. The report stated, "It is evident in a series of measurements from Florida that SN_{40} decreases to a minimum value by about midyear and then increases, as contrasted with Texas during a dry year, when there is very little, if any, time-of-year effect [see Appendix F]." (22)

The effect of pavement temperature on skid number can be further analyzed by a model developed by the Pennsylvania researchers. The researchers developed and validated procedures for normalizing pavement friction measurements for seasonal and short-term variations. A generalized predictor model was developed from the statistical analysis of skid resistance measurements taken frequently during the season in three geographic areas. With realistic temperature variations, this model resulted in only slight and inconsistent variations of SN_{40} with pavement temperature. This slight variation was evident from graphs of the data from Florida, New York, Pennsylvania, and San Angelo, Texas (see Appendix F). (22) Therefore, this research supports the conclusion that pavement temperature does not significantly affect pavement skid resistance.

A statement by Kennedy, et al. from Britain, partially supports the position that a temperature correction factor is not necessary for skid-testing in the U.S. (in accordance with ASTM Method E-274). Kennedy stated,

> Increasing the (pavement) temperature reduces SFC by about 0.003 units per °C but surfacings with a higher coefficient of friction tend to suffer a greater reduction. The effect is not particularly significant over the normal working range of temperatures in a particular area, but can be significant when equipment with noncontinuous types of operation is used; systems with continuous measurement of skid resistance need only to ensure that equilibrium working temperatures have been reached, normally by testing for about 500 m (1640 ft), prior to recording on the survey lengths. (10)

The testing method in the U.S. is not continuous; however, because the locked test wheel is allowed to slide on the pavement for a certain distance to permit the temperature in the contact area to stabilize, it could be argued that equilibrium temperatures are reached and a correction factor is not necessary.

Furthermore, when the pavement temperature is high, it is brought down to an equilibrium temperature by the ambient temperature of the water that is applied to the pavement ahead of the wheel before and during wheel lockup. This is further justification for not applying a correction factor for pavement temperature.

Machine Error Effects

In 1967, when NCHRP Report 37 was published, the national Field Test and Evaluation Centers (FT & EC) had not yet been established. Not until 1971 did the Federal Highway Administration (FHWA) establish the centers to calibrate and correlate locked-wheel skid trailers in order to reduce interstate variations in locked-wheel skid measurements of pavement surfaces. (20)

In NCHRP Report 151 (1974), "Locked-Wheel Pavement Skid-Tester Correlation and Calibration Techniques," the standard deviation of mean skid numbers was reduced from 4.08 to 1.04 after corrective measures, including calibrations, were applied. The factors thought to be most responsible for the initially poor correlation were, in order of decreasing effect, force calibration and wheel load errors, chart interpretation and evaluation, watering systems, and temperature effects. Because of NCHRP Report 151's findings, significant improvements were

made in methods that could be controlled—these methods included all those stated above except temperature.

The NCHRP Report 151 listed the error sources in skid-testing and the estimated error bands at 40 mph (as shown in Appendix H, Table 1). From these estimates, the predicted total error band for inventory testing by a single tester was calculated to be 2.4 SN for the "reduced" condition (as shown in Appendix H, Table 2). Reduced refers to the decrease in errors resulting from improved procedures, correction of data, and improved equipment. (13)

Furthermore, the allowable machine error stated in ASTM E-274 is a standard deviation of 2 SN. Using a one-sided 95 percent confidence interval, the calculated machine error is (2) (1.645) = 3.29 (or approximately 3).

Given the improved and standardized calibration procedures described above, the machine error correction factor can safely be decreased to 3 SN.

Speed Gradient

The WSDOT mean speed gradient (G) is 0.2 SN/mph versus the G = 0.5 SN/mph in NCHRP Report 37. This is based on calibration equations developed at TTI (as shown in Appendix I).

REVISED SKID NUMBER

On the basis of the findings discussed above, the correction factor for temperature effects (6 SN) can be deleted and the correction factor for machine errors (5 SN) can be decreased to 3 SN. The result is as follows:

$$SN = SN_0 + 3$$

$$SN \text{ (at } V = 50 \text{ mph)} = 20.5 + 3 = 23.5$$

$$SN \text{ (rounded)} = 24$$

$$SN_{40} = SN \text{ (rounded)} + [0.2 \text{ SN/mph} \times (V - 40 \text{ mph})]$$

$$SN_{40} = 24 + [0.2 \text{ SN/mph} \times (50 - 40 \text{ mph})]$$

$$SN_{40} = 24 + 2 = 26$$

The revised minimum skid number is SN_{40} = 26 (revised in that it is derived using the NCHRP methodology with improved inputs).

CHAPTER 4

SUMMARY

GUIDELINE

This paper examined NCHRP Report 37 (1967), which set a recommended minimum skid number guideline of 37 for highways. Adjustments were made to the NCHRP Report 37 methodology for current knowledge in the areas of pavement temperature and machine errors and their effect on pavement skid resistance. The resulting minimum skid number guideline was calculated to be 26.

WSDOT uses AASHTO terminology, which assigns friction number (FN) to represent the identical measured value of skid resistance as SN. Therefore, the recommended minimum friction number guideline for WSDOT is 26. A CALTRANS report (18) concluded that the accident rate was nearly constant on pavements with friction numbers greater than 26, but increased substantially as the friction numbers decreased from 25 to 17. This supports the suggested guideline.

State DOT's have generally not assigned a single minimum friction value as policy for highway skid resistance. The issue is difficult because of the number of factors affecting the availability of skid resistance (as described in the Background section, Chapter 1) and sensitive because highway departments should be concerned with pavements in real need of surface friction improvement. Consequently, state DOT's generally prefer to use a range of friction values.

USE OF SMOOTH AND RIBBED STANDARD TEST TIRES FOR NETWORK TESTING

Given the research results by Henry and Wambolt (8) on the smooth tire procedure for routine skid-testing (ASTM E-524 or AASHTO M-286), this measurement process appears promising. Their research demonstrated that if only one tire is used, it should be the smooth tire

because of its equal sensitivity to micro- and macro-texture. Adjustments must be made to the recommendations of this report if a smooth tire is used.

LIMITATIONS OF USING FN ALONE FOR PAVEMENT MANAGEMENT DECISIONS

It is essential to remember that roads should not be ranked by friction number only. Consider the example of a long, straight road with a friction number of 25 and an ADT of 1. This road should not be a concern if many other roads have high ADT values, curves, intersections, etc., and have the same or even higher FN values. These roads would be more likely to have wet weather accidents.

In fact, WSDOT must analyze wet-pavement accident rates first, before skid resistance data, when preparing the list of hazardous sites by priority order. This is recommended by FHWA Technical Advisory T5040.17 (as shown in Appendix J). (31)

Finally, to fully evaluate the risk of a wet-pavement accident, all factors that influence demand for friction and available friction must be considered. This is difficult because wet-pavement accidents are caused by complex interactions among many roadway, vehicle, human, and environmental factors. Accidents also occur because of unpredictable factors such as inattentiveness, misjudgment, recklessness, and random variables such as unforeseeable events or obstacles. Realizing this, pavement engineers do their best to provide reasonably safe highways through routine skid-testing and experience. (1)

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I wish to thank Newton Jackson, Keith Anderson and Linda Pierce of the Washington State Department of Transportation (WSDOT) for their cooperation and assistance in conducting this research. Also instrumental was Jeffrey Donahue, the Transportation Engineer in charge of operation and maintenance of WSDOT's skid trailer, and his crew.

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APPENDIX A

SUMMARY OF FACTORS IN SKID RESISTANCE MEASUREMENT (FROM MEYER, ET AL. [13])

ERROR SOURCE RANDOM	SYSTEMATIC		MAXIMUM EFFECT	AVERAGE ERROR BAND FACTOR	AVERAGE ERROR BAND SKID RESISTANCE	CORRECTIVE ACTION	REDUCED ERROR BAND FACTOR	REDUCED ERROR BAND SKID RESISTANCE
X		Speed holding (1) *	At 40 mph ±1.2 SN per mph	±2 mph	±1.5 SN	Speed deviation indicator	±1 mph	±0.8 SN
	X	Speed measurement (1)	Same	±5%	±1.5 SN	Fifth wheel and a) tachometer-generator b) pulse-generator	±2% ±0.5%	±0.8 SN ±0.2 SN
	X	Water temperature (1)	Negligible					
	X	Air temperature (2)	Indirect effect through pavement and tire temperature.					
X		Pavement or tire temperature (2)	±4%/10° F	Depends on season and geographical region	±2%/10° F	Correction requires accurate skid resistance and temperature measurement		±1%/10°F
X	X	Water film (3)	±1 SN for ±10% variation	±25%	Negligible on most pavements, on some ±2.5 SN	Specify calibration method, reduce tolerance to ±5%	±5%	Negligible on most pavements, on some ±1 SN
	X	Water flow (3)	Strong	Large		Uniform watering system, calibrated flow rate proportional to speed		Negligible
X		Pavement variability, (4) lateral	10 SN	15 in.	±4 SN	Operator awareness	5 in.	±2 SN
X		Pavement variability, (4) longitudinal	7 SN in mile		±2 SN	Number of samples (wheel-locks) per test based on standard deviation of tester		±2 SN
X		Conditioning and deterioration (4)	4 SN per day		−2 SN	Run control tests, randomize test sequence, correct data		−1 SN
	X	Tire variability (5)	2.5 SN		±1 SN	Check before use		±0.5 SN
	X	Tire construction (5)	2 SN		±1 SN	Belted tire		±0.5 SN
	X	Tire condition (5)	Within wear range 1 SN		±1 SN	Check for uniform wear		±1 SN
	X	Inflation pressure (5)	1 SN in operating range	24 to 28 psi	1 SN	Use reliable gage		1 SN
	X	Wheel-load error (6)	% SN error equal to % weight error	±2%	±2%	Use scale of minimum resolution of 5 lb	±0.5%	±0.5%
	X	Wheel-load range (6)	1 SN/100 lb	880 to 1080 lb	2 SN	Reduce range		1 SN

ERROR SOURCE RANDOM	SYSTEMATIC		MAXIMUM EFFECT	AVERAGE ERROR BAND FACTOR	AVERAGE ERROR BAND SKID RESISTANCE	CORRECTIVE ACTION	REDUCED ERROR BAND FACTOR	REDUCED ERROR BAND SKID RESISTANCE
X		Dynamic wheel-load change (6)	2 SN		±1 SN	Avoid aerodynamic loads, wheel-load recording with electronic evaluation		±0.5 SN
X	X	Instrumentation (7)	Drift		10% or more	Reliable instrumentation, observing operating procedure		±1%
X	X	Operating procedure (8)		Controls other error sources		Follow correct procedure		
	X	Torque calibration (9)	Negligible			See procedure		±0.5% (±2 lb)
	X	Platform calibration (9)	±10%		±4.5%	See procedure		±2% (±5 lb)
X	X	Data eval.: (10) Operator	±5 SN		±3 SN	Adequate resolution, correct operating procedure		±1 SN
	X	Braking cycle	±2%	Minimum cycle 2 sec	±2%	Optimal filtering increase interval	Minimum cycle 3 sec	±1%
X		Dynamics (11)	Negligible direct effect					
		Statistical control (12)		Repeat tests		Estimate standard deviation of tester, determine number of repeat tests	Repeat tests	

* Numbers indicate corresponding sections in Appendix A.

APPENDIX B

WSDOT MEMORANDUM REGARDING PAVEMENT FRICTION INVENTORY (FROM WSDOT STATEWIDE FRICTION INVENTORY [26])

Washington State
Department of Transportation

INTRA-DEPARTMENTAL COMMUNIC

DATE: December 11, 1989

FROM: D.J. Vandehey/John R. Strada JS

PHONE: SCAN 753-7103

SUBJECT: Pavement Friction Inventory - 1989

TO: D.S. Senn
G.F. Demich
M.D. Tranum

Attached is an inventory of pavement friction tests performed on the state highways in your District as specified in the Departmental Position Statement entitled "Skid Accident Reduction Program." This test report is an update of our last pavement friction inventory (1988) and covers the period from March through July 1989.

Approximately one-half of the entire State highway system is tested for pavement friction each year - Districts 1, 3 and 5 on even-numbered years and Districts 2, 4 and 6 on odd-numbered years. We are submitting to each District only the data that pertains to that specific District.

When comparing the pavement friction values from one reporting period to another, check the lane and direction of testing for best comparison. The ADT shown at each milepost is from the 1988 traffic data obtained from both directions. On overlays or reconstruction, the test data should enable a determination of whether the friction test was conducted before or after the new pavement was placed.

Establishing minimum levels of pavement friction for all types of surfaces still continues to be a subject of debate by several agencies nationwide. Our position remains the same, and until the national research is completed and the results are accepted by a majority of the states, we will continue to suggest a desirable minimum friction number of 35 and further advise that those areas with friction numbers below 40 should be monitored for indications of potential hazards. The inventory listing specifically delineates those particular areas with values of 0 to 34 and 35 to 39.

This inventory represents testing on all State highways within your District at each milepost. Occasionally, conditions will prevent doing the test at the milepost. Should you desire special testing or further information, please contact Bob Allison (SCAN 234-4664) at the Materials Lab.

APPENDIX C

DYNAMIC CALIBRATION RUN—SKID TESTER OUTPUT WITH DATA DEFINITIONS AND GRAPH OF FRICTION NUMBER VS. TEST NUMBER (FROM TEXAS TRANSPORTATION INSTITUTE [21])

PAVEMENT SKID TESTER

DISTRICT 23 CONTROL SECTION 0000 ROUTE 005 WEATHER 1 03/01/93

PATH	POSTD	LANE	# LNS	SURF	MISC	DIRCT	INCLN	TEMP	TF RO AR CC TE	VF EO RR TC E	PC EO AE KF	AS DK JI D	US NK AI DD J	SPEED	TO ED SO TM	FLOW	LA AC TC RE LL	CASST	ERRS
2	65	1	2	1		2	-85	7	504	1006	827	499	502	39	91997	260	46		
2	65	1	2	1		2	-65	9	516	1008	827	509	512	39	91898	259	46		
2	65	1	2	1		2	-35	9	541	1015	821	531	534	40	91798	261	46		
2	65	1	2	1		2	-85	6	537	1005	846	531	534	39	91698	260	46		
2	65	1	2	1		2	-85	9	541	1000	821	538	541	40	91597	260	46		
2	65	1	2	1		2	-65	9	525	1015	862	515	518	41	91497	260	46		
2	65	1	2	1		2	-85	9	512	984	860	518	521	41	91376	267	46		
2	65	1	2	1		2	-65	9	520	988	896	524	527	39	91297	261	46		
2	65	1	2	1		2	-65	9	532	1011	887	522	525	41	91197	261	46		
2	65	1	2	1		2	-65	9	516	1002	864	512	515	41	91096	271	46		
2	65	1	2	1		2	-85	7	521	999	908	520	523	39	90997	260	46		

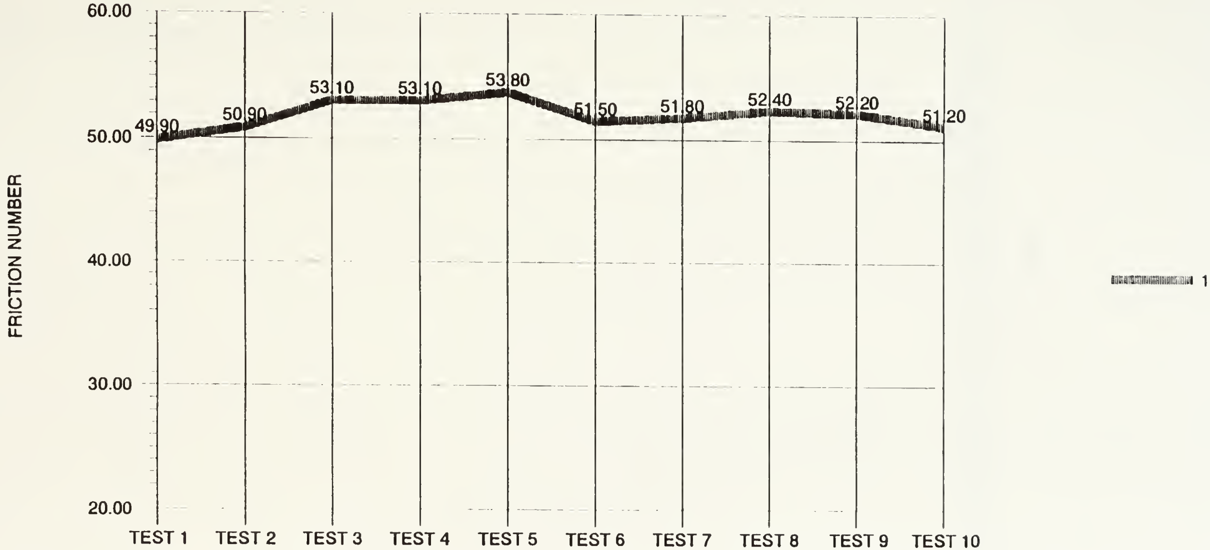
PAVEMENT SKID TESTER DATA DEFINITIONS

The Pavement Skid Tester generates printed reports and records test data onto a digital cassette. This data includes parameters that are operator entered as well as values that are derived from the test instrumentation. Below is a tabulation of these parameters and their meanings.

Parameter	Definition
District	Departmental district: 0-99
Control Section	Control section number: 0-9999
Route	Highway route number: 0-999
Weather	Weather code: 0 = clear 1 = cloudy 2 = rain 3 = windy
Month	Month: 1-12
Day	Day: 1-31
Year	Last digits of year: 0-99
Wheel Path	Wheel path: 1 = right 2 = left
Posted Speed	Posted speed limit
Lane	Lane number: 0-9
Total Lanes	Total number of lanes: 0-9
Surface	Surface description number: 0-9 0 = patch 1 = dense graded AC 2 = open graded AC 3 = chip seal 4 = PCC 5 = PCC grooved 6 = epoxy 7 = slurry seal 8 = non aggregate seal 9 = all others
Misc	Miscellaneous: 0-9

Parameter	Definition
Direction	Direction: 1 = north (incrementing) 2 = south (decrementing) 3 = east (incrementing) 4 = west (decrementing)
Inclination	Inclination of trailer in degrees. Blue momentary controller cabinet button selects transverse inclinometer. Otherwise reads longitudinal inclination. Readings are updated only when testing is not active. Very closely spaced tests may cause this value to lag quickly changing conditions.
Temperature	Measured temperature in degrees C
Tract Force	Measured traction force in pounds
Wheel Load	Measured vertical force in pounds
Adj Skid	Skid number = traction / vertical × 100 adjusted by calibration equation
Unadj Skid	Skid number = traction / vertical × 100
Test Speed	Measured test speed
Test Odom	Odometer at the center of the data averaging segment
Flow Rate	Average measured flow rate during test
Lateral Accel	Lateral Acceleration in Gs from accelerometer

DAILY FRICTION GRAPH DATE 03/06/93
SR 5 MP 92.00



1 = F.N. EACH TEST AVG. TEST = 40 MPH
AVG. - RANGE -
51.99 MIN 49.90 MAX 53.80

APPENDIX D

GREAT BRITAIN SKID RESISTANCE POLICY FOR DIFFERENT CATEGORIES OF SITE (FROM GARGETT [5])

problem associated with low skidding resistance, surface treatment or treatments are to be determined and cost and economic appraisals undertaken. Sites will then be short-listed in order of priority to enable funds to be allocated to the best effect. If, however, following the Site Investigation, treatment is not considered necessary, the site will not be short-listed, but kept under review.

Signs warning that the road is slippery are to be erected at all sites found to be at or below the investigatory level, until such time as surface treatments have been completed or the site investigation confirms that surface treatments are not required.

Conclusion

This paper has outlined the work undertaken to develop the skidding-resistance policy which is to be applied to the whole of the trunk-road network in Great Britain.

TABLE 1—*Investigatory skidding resistance levels for different categories of site (based on average sites, but see Departmental Advice Note HA 36/87, Section 6; additional advice).*

Site Category	Site Definition	Investigatory Levels $MSSC_{50}$ (at 50 km/h) or Equivalent (top) and Corresponding Risk Rating (bottom)							
		0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
		1	2	3	4	5	6	7	8
A	motorway (mainline)		▨						
B	dual carriageway (all-purpose)—non-event sections		▨						
C	single carriageway—non-event sections			▨					
D	dual carriageway (all-purpose)—minor junctions			▨					
E	single carriageway—minor junctions				▨				
F	approaches to and across major junctions (all limbs)				▨				
G1	gradient 5% to 10%, longer than 50 m dual (downhill only) single (uphill and downhill)				▨				
G2	gradient steeper than 10%, longer than 50 m dual (downhill only) single (uphill and downhill)					▨			
H1	bend (not subject to 40 mph or lower speed limit) radius ≤ 250 m				▨				
J	approach to roundabout						▨		
K	approach to traffic signals, pedestrian crossings, railway-level crossings or similar						▨		

TABLE 1—*Continued*

Site Category	Site Definition	Investigatory Levels $MSSC_{20}$ (at 20 km/h) or Equivalent (top) and Corresponding Risk Rating (bottom)							
		0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75
		1	2	3	4	5	6	7	8
H2	bend (not subject to 40 mph or lower speed limit) radius ≤ 100m					▨			
L	roundabout				▨				

▨ Investigatory Levels

NOTES:

(a) Investigatory levels are for the *mean* skidding resistance within the appropriate section length.
(b) Investigatory levels for site categories A, B, and C are based on 100-m section lengths.
(c) Investigatory levels for site categories D, E, F, J, and K are based on the 50-m approach to the feature.
(d) Investigatory levels for site categories G and H are based on 50 m section lengths, or for H the length of the curve if shorter.
(e) The Investigatory level for site category L is based on 10-m section lengths.
(f) Residual section lengths less that 50% of a complete section should be attached to the penultimate section.
(g) Individual values within each section should be examined, and the significance of any values which are substantially lower than the mean value assessed.
(h) No precise definitions of Major/Minor Junctions have been included since judgment will have an important input.

In England alone, additional expenditure of £9 million each year is proposed during the four-year period to bring the network to the levels required by the policy; thereafter, there is a continuing commitment of £2.5 million each year to maintain the roads at these levels. However, at these levels, annual accident savings valued at £35 million will be achieved, making this a very cost-effective accident prevention measure.

Acknowledgments

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APPENDIX E

MARYLAND REPORT - CORRELATION BETWEEN PAVEMENT TEMPERATURE AND FRICTION NUMBER AND GRAPHS OF FRICTION NUMBER VS. PAVEMENT TEMPERATURE (FROM MITCHELL, ET AL. [14])

CORRELATION BETWEEN PAVEMENT TEMPERATURE

AND FRICTION NUMBERS

Site Number		Pavement Type	Correlation Coefficient (R)	Slope
1		JRCP	.2060	-.0330
2		JRCP	.0801	.0150
3		JRCP	.0049	.0007
	Average		.0970	-.0058
4		CRCP	.2174	.0378
5		CRCP	.1280	.0173
15		CRCP	.0527	-.0160
16		CRCP	.1025	.0273
19		CRCP	.0041	-.0009
20		CRCP	.1031	.0191
	Average		.1013	+.0141
6		DGBC	.0150	-.0004
7		DGBC	.0881	.0205
8		DGBC	.0144	.0029
9		DGBC	.2425	-.0417
10		DGBC	.2078	.0457
11		DGBC	.1141	.0301
12		DGBC	.0911	-.0264
	Average		.1104	+.0044
13		OGBC	.0773	.0289
14		OGBC	.0863	.0467
17		OGBC	.1577	.0555
18		OGBC	.0223	.0072
	Average		.0859	+.0346

RIGID

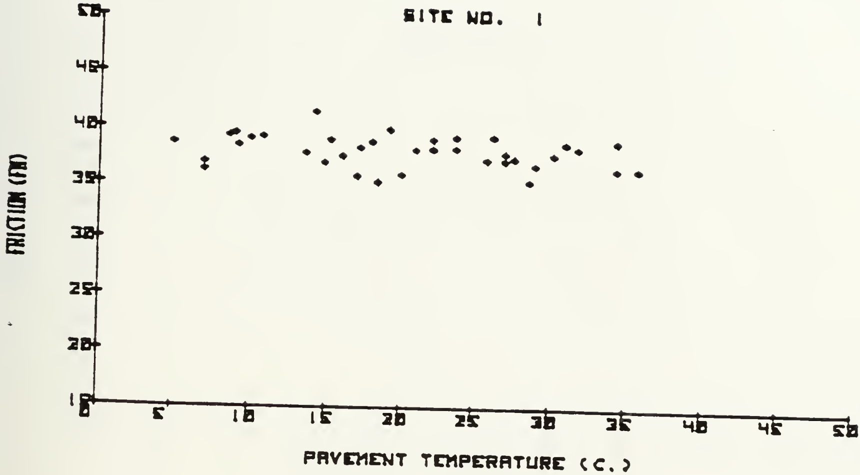
Jointed Reinforced Concrete Pavement (JRCP)

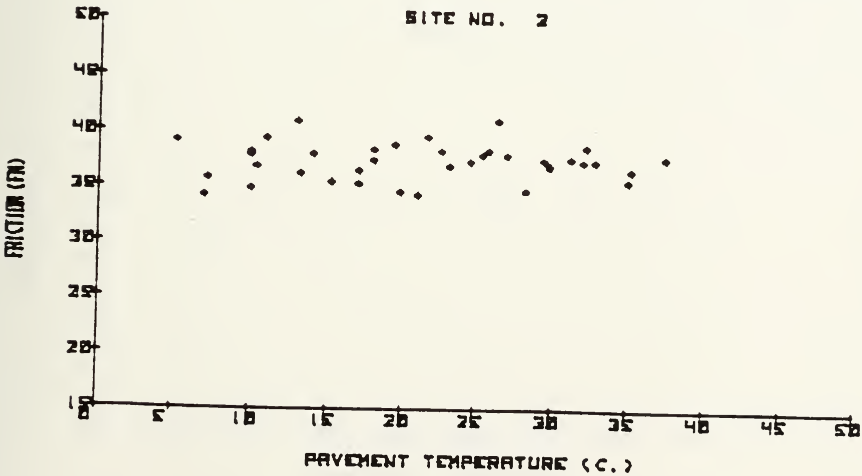
Continuously Reinforced Concrete Pavement (CRCP)

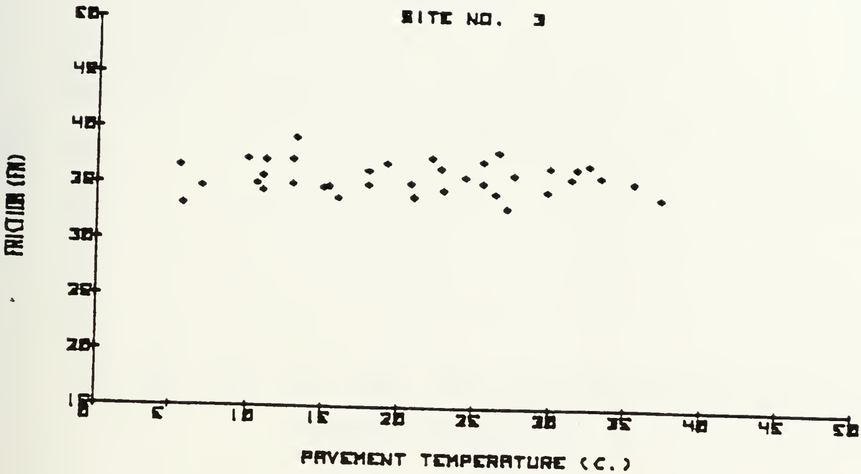
FLEXIBLE

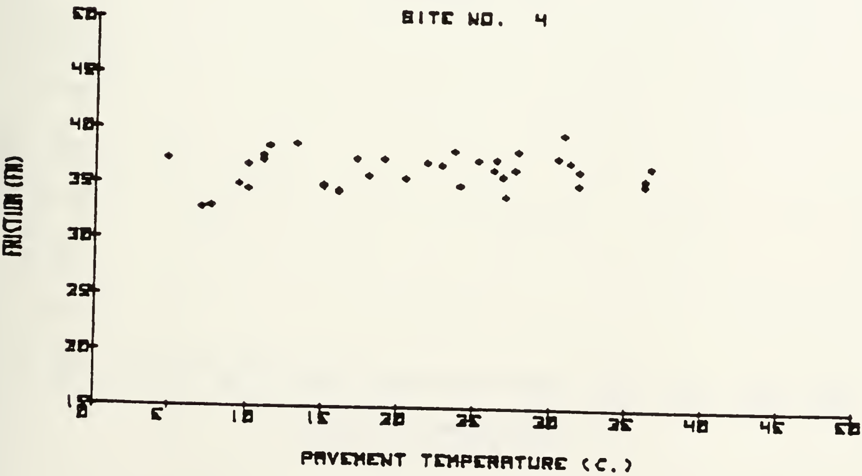
Dense Graded Bituminous Concrete Pavement (DGBC)

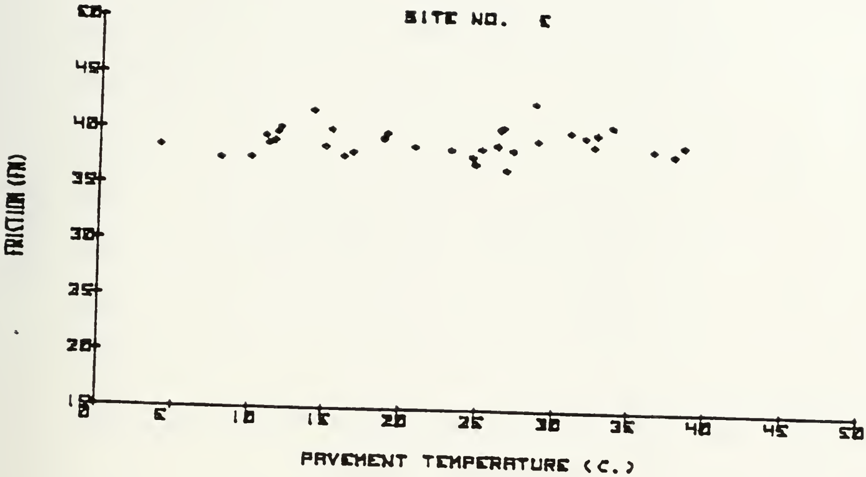
Open Graded Bituminous Concrete Pavement (OGBC)

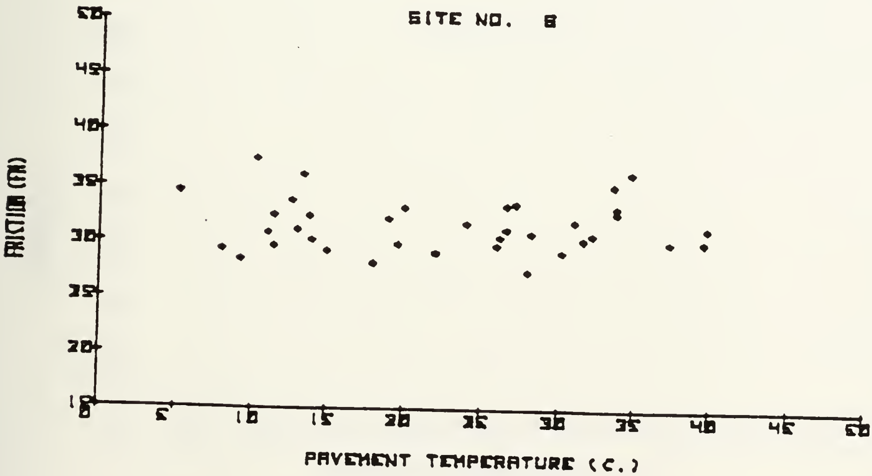

SITE NO. 1
FRICTION (FN)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
30
35
40
45
50
PAVEMENT TEMPERATURE (C.)

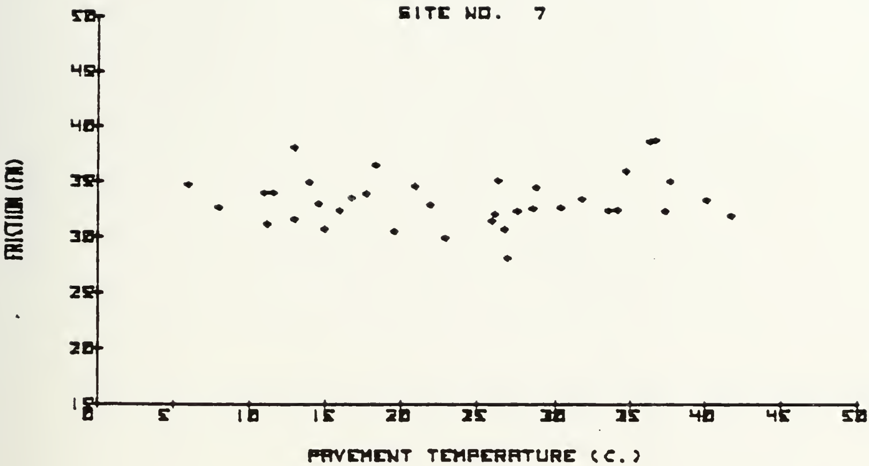

SITE NO. 2
FRICTION (FN)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
30
35
40
45
50
PAVEMENT TEMPERATURE (C.)

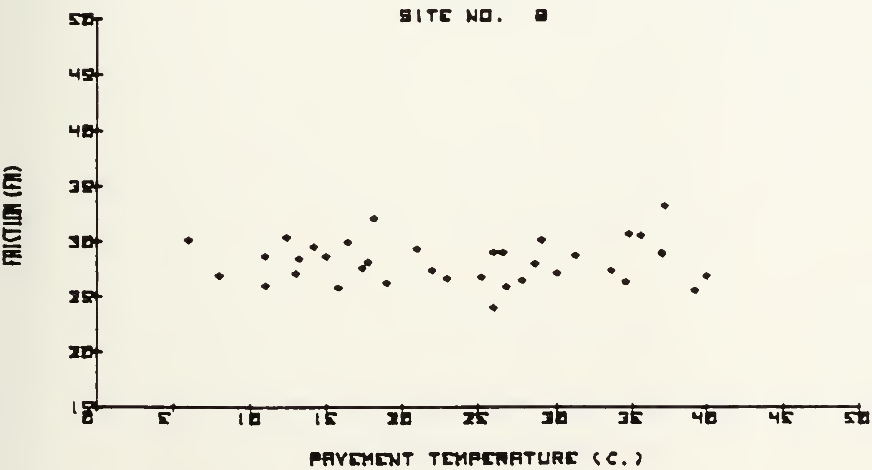

SITE NO. 3
FRICTION (FN)
PAVEMENT TEMPERATURE (C.)


SITE NO. 4
FRICTION (FN)
PAVEMENT TEMPERATURE (C.)


SITE NO. 5
FRICTION (FN)
PAVEMENT TEMPERATURE (C.)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
30
35
40
45
50


SITE NO. 6
FRICTION (FN)
PAVEMENT TEMPERATURE (C.)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
30
35
40
45
50


SITE NO. 7
FRICTION (FN)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
30
35
40
45
50
PAVEMENT TEMPERATURE (C.)


SITE NO. 8
FRICTION (FN)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
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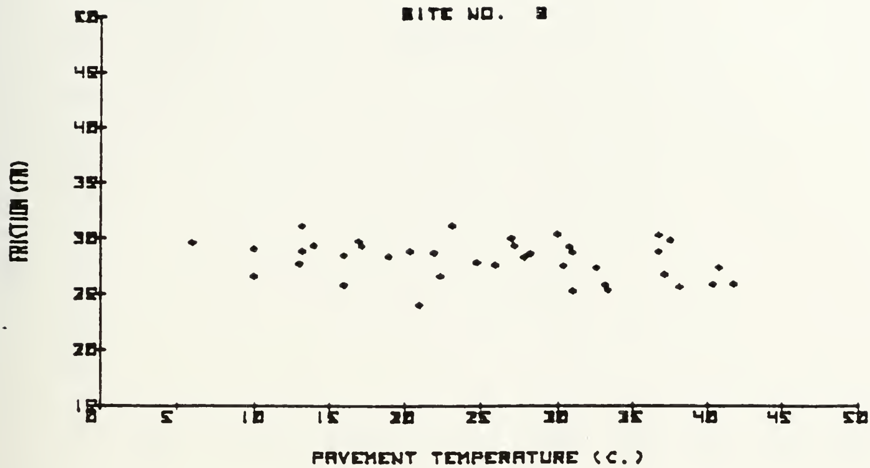
35
40
45
50
PAVEMENT TEMPERATURE (C.)


SITE NO. 9
FRICTION (FN)
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45
40
35
30
25
20
15
0
5
10
15
20
25
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35
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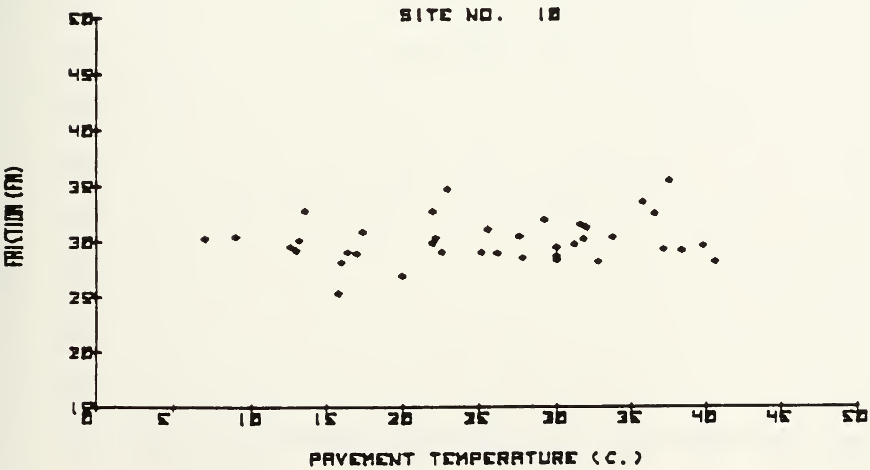
45
50
PAVEMENT TEMPERATURE (C.)


SITE NO. 10
FRICTION (FN)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
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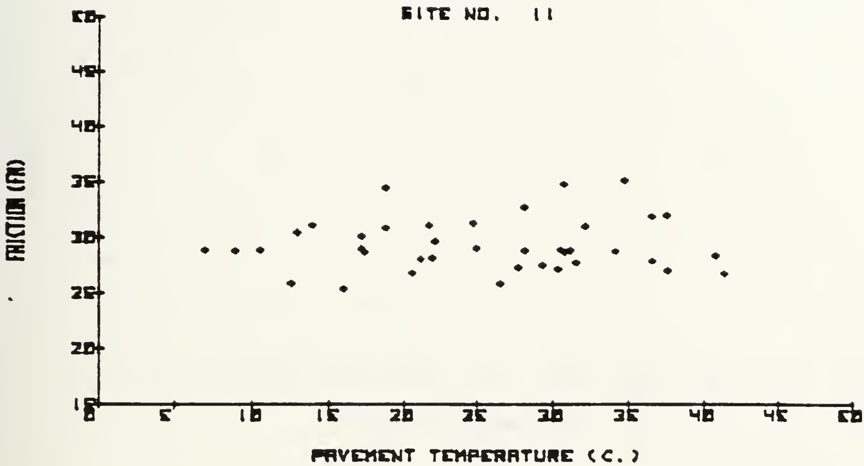
35
40
45
50
PAVEMENT TEMPERATURE (C.)


SITE NO. 11
FRICTION (FN)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
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35
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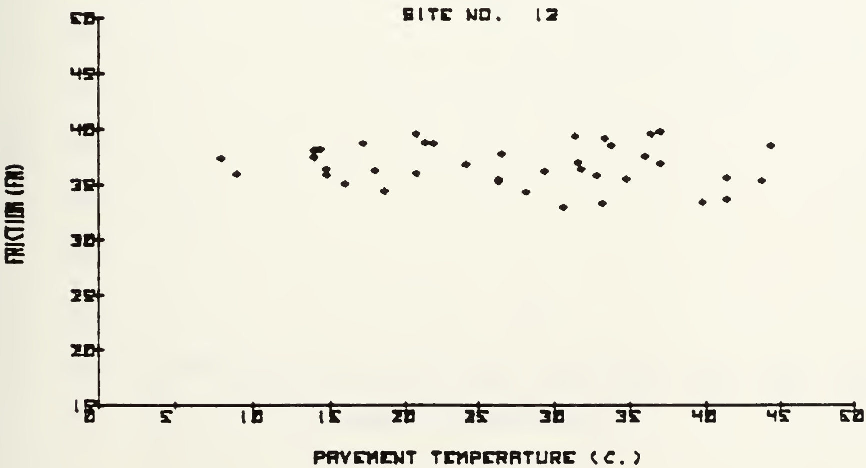
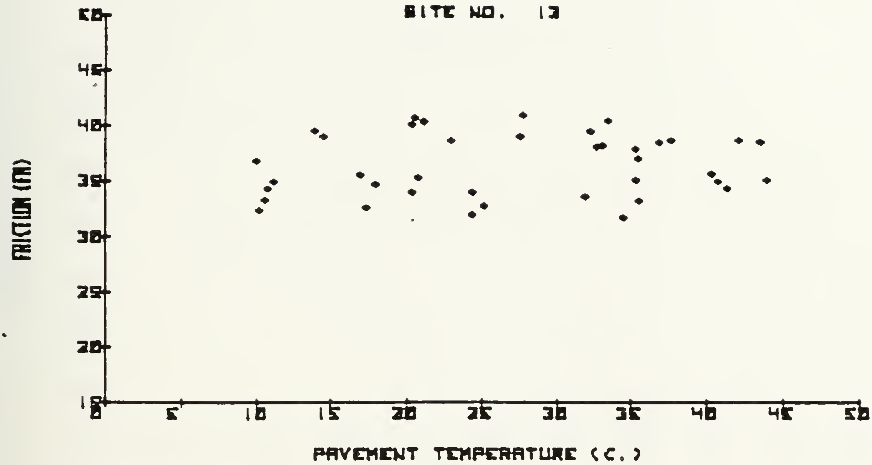
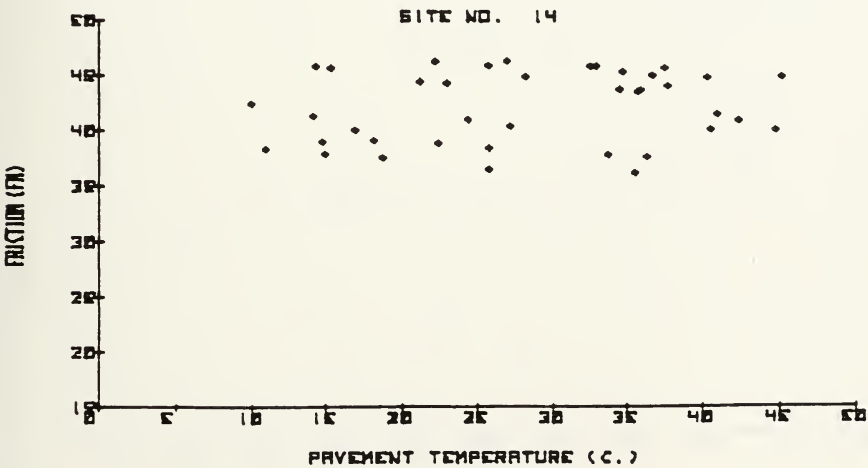
45
50
PAVEMENT TEMPERATURE (C.)


SITE NO. 12
FRICTION (FN)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
30
35
40
45
50
PAVEMENT TEMPERATURE (C.)


SITE NO. 13
FRICTION (FN)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
30
35
40
45
50
PAVEMENT TEMPERATURE (C.)


SITE NO. 14
FRICTION (FN)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
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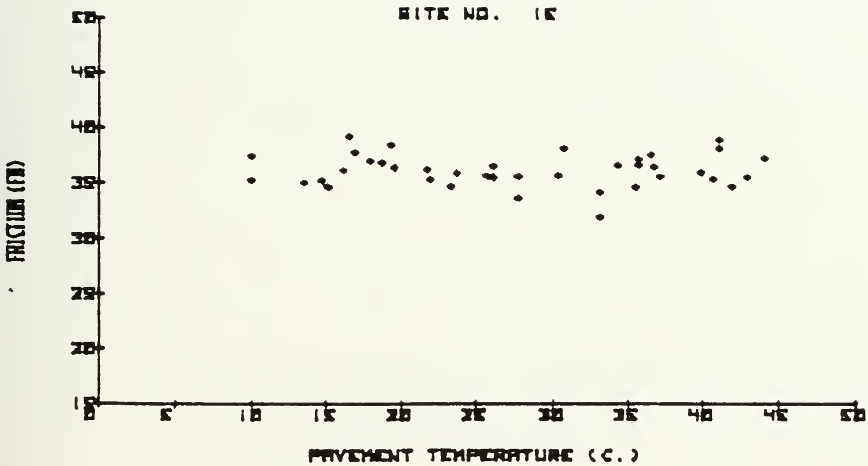
35
40
45
50
PAVEMENT TEMPERATURE (C.)


SITE NO. 15
FRICTION (FN)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
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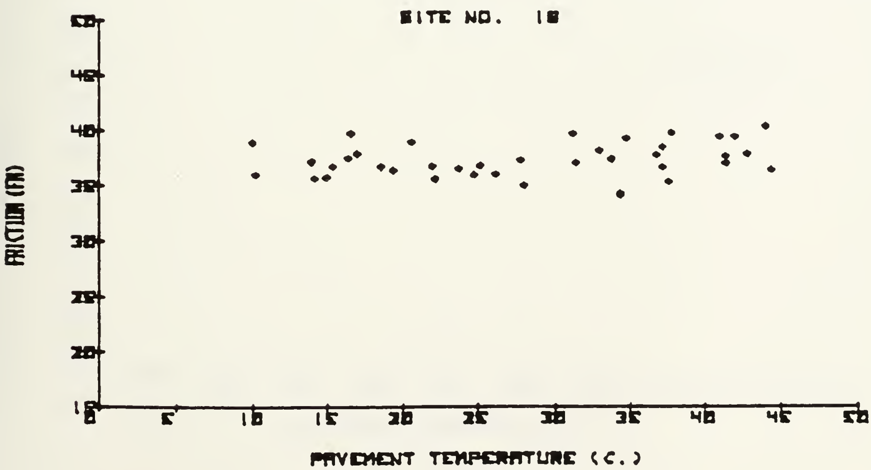
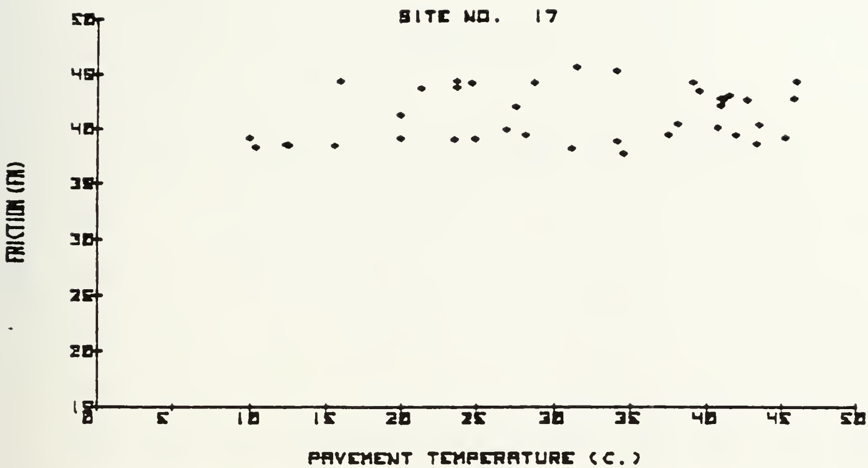
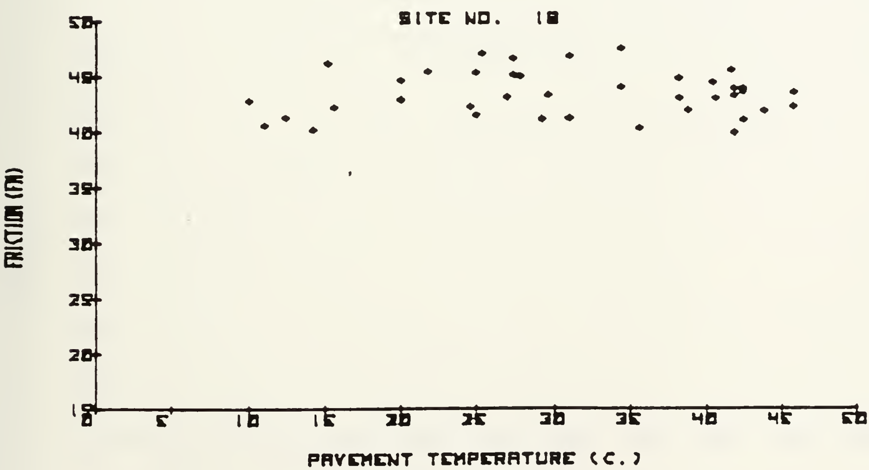
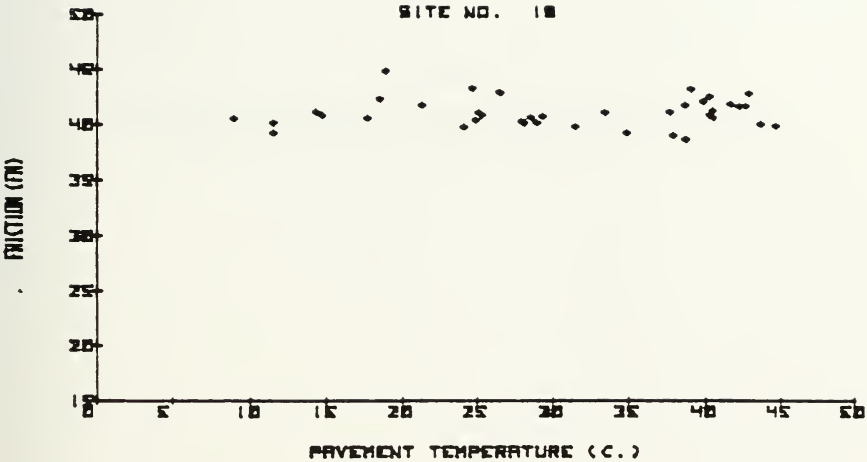
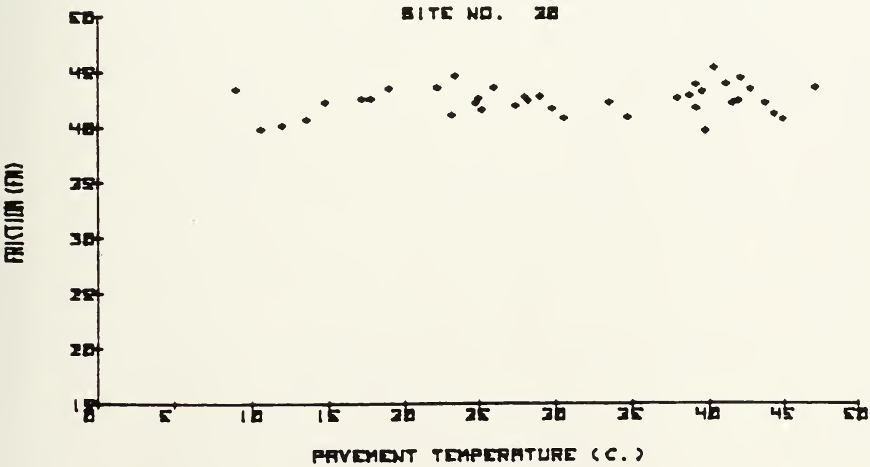
35
40
45
50
PAVEMENT TEMPERATURE (C.)


SITE NO. 16
FRICTION (FN)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
30
35
40
45
50
PAVEMENT TEMPERATURE (C.)


SITE NO. 17
FRICTION (FN)
PAVEMENT TEMPERATURE (C.)


SITE NO. 18
FRICTION (FN)
PAVEMENT TEMPERATURE (C.)


SITE NO. 18
FRICTION (FN)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
30
35
40
45
50
PAVEMENT TEMPERATURE (C.)


SITE NO. 28
FRICTION (FN)
50
45
40
35
30
25
20
15
0
5
10
15
20
25
30
35
40
45
50
PAVEMENT TEMPERATURE (C.)

APPENDIX F

PENNSYLVANIA REPORT - SKID RESISTANCE BY DAYS FOR FLORIDA AND TEXAS (FROM WAMBOLT, ET AL. [22])

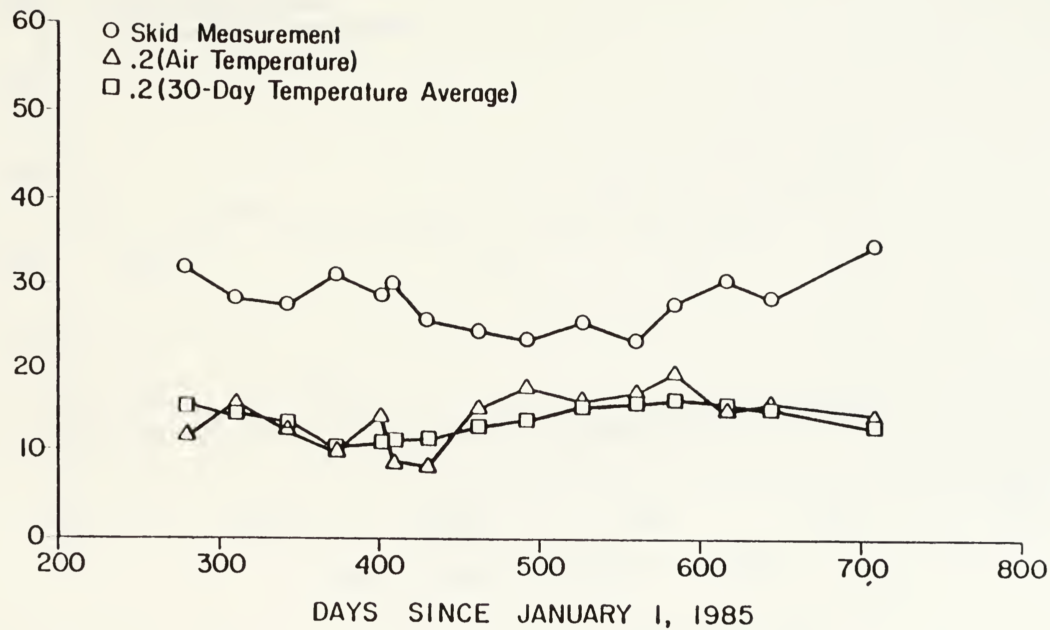


Figure G-1. Skid Resistance by Days for Florida

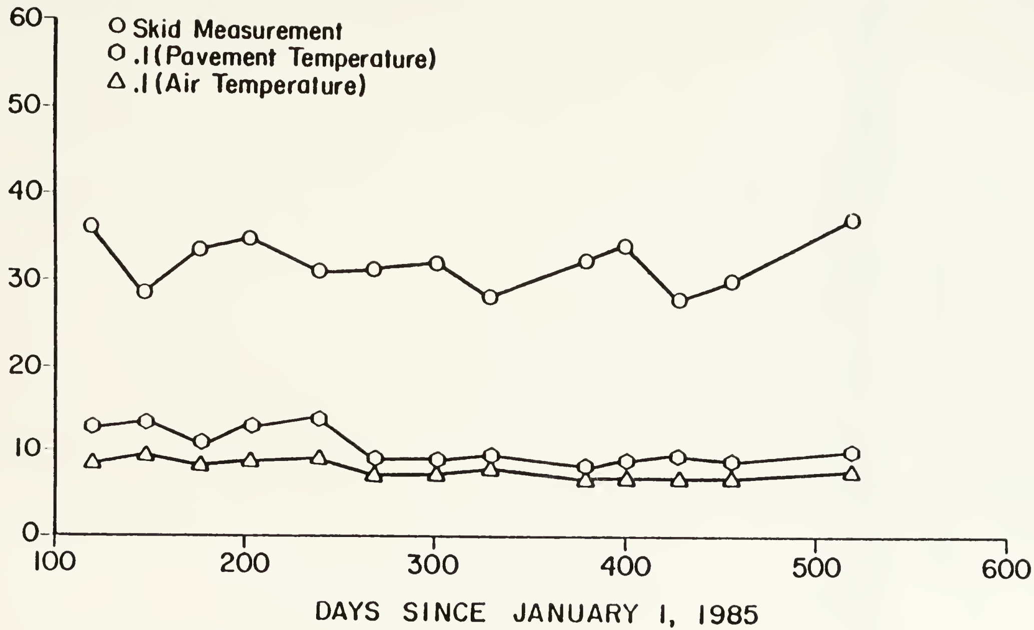


Figure G-2. Skid Resistance by Days for San Angelo, Texas

APPENDIX G

PENNSYLVANIA REPORT - SKID RESISTANCE GRAPHS AND DATA SETS FOR FLORIDA, NEW YORK, PENNSYLVANIA, AND TEXAS (FROM WAMBOLT, ET AL. [22])

LEGEND

S = skid resistance (rib tire)

A = 0.2 × air temperature

3 = 0.2 × T30

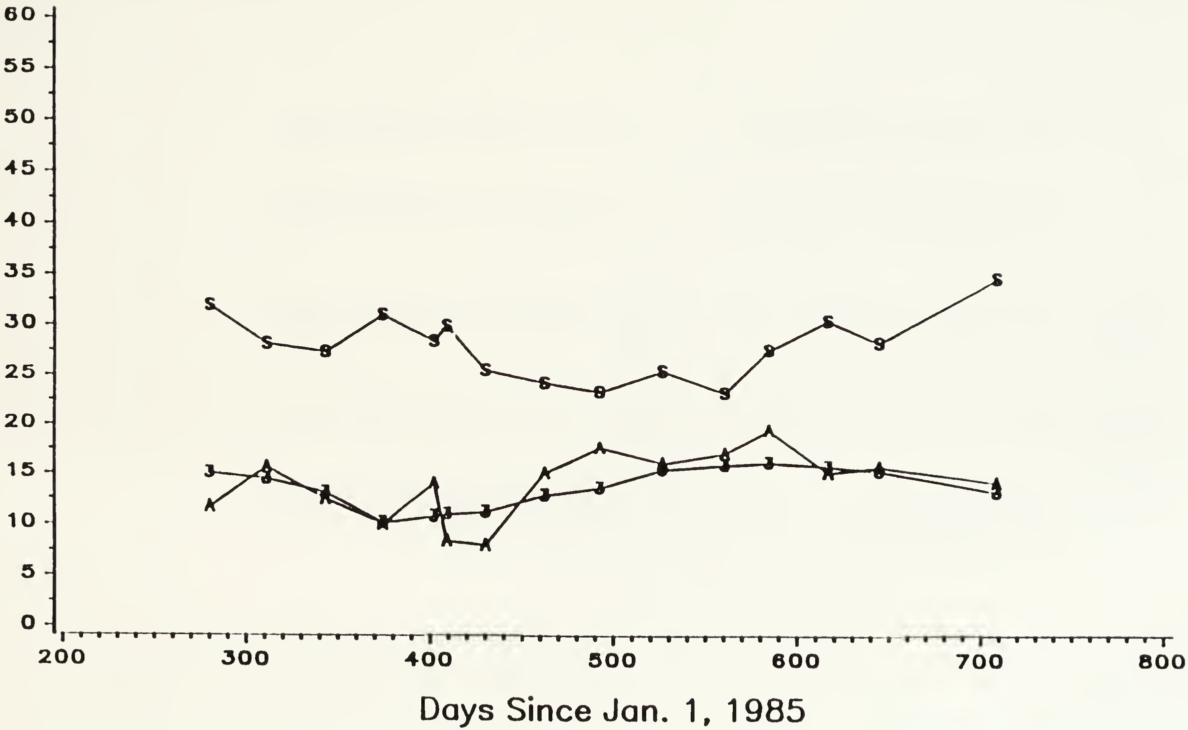
T30 = average temperature for prior 30 days

DSFN = dry spell factor (number of days since rainfall of 0.1 inch or more)

SKID RESISTANCE BY DAYS FOR FLORIDA

RIB TIRES. DATE MAY 19, 1987 S=SKID NO. A=.2*AIR TEMP.

SITE=1



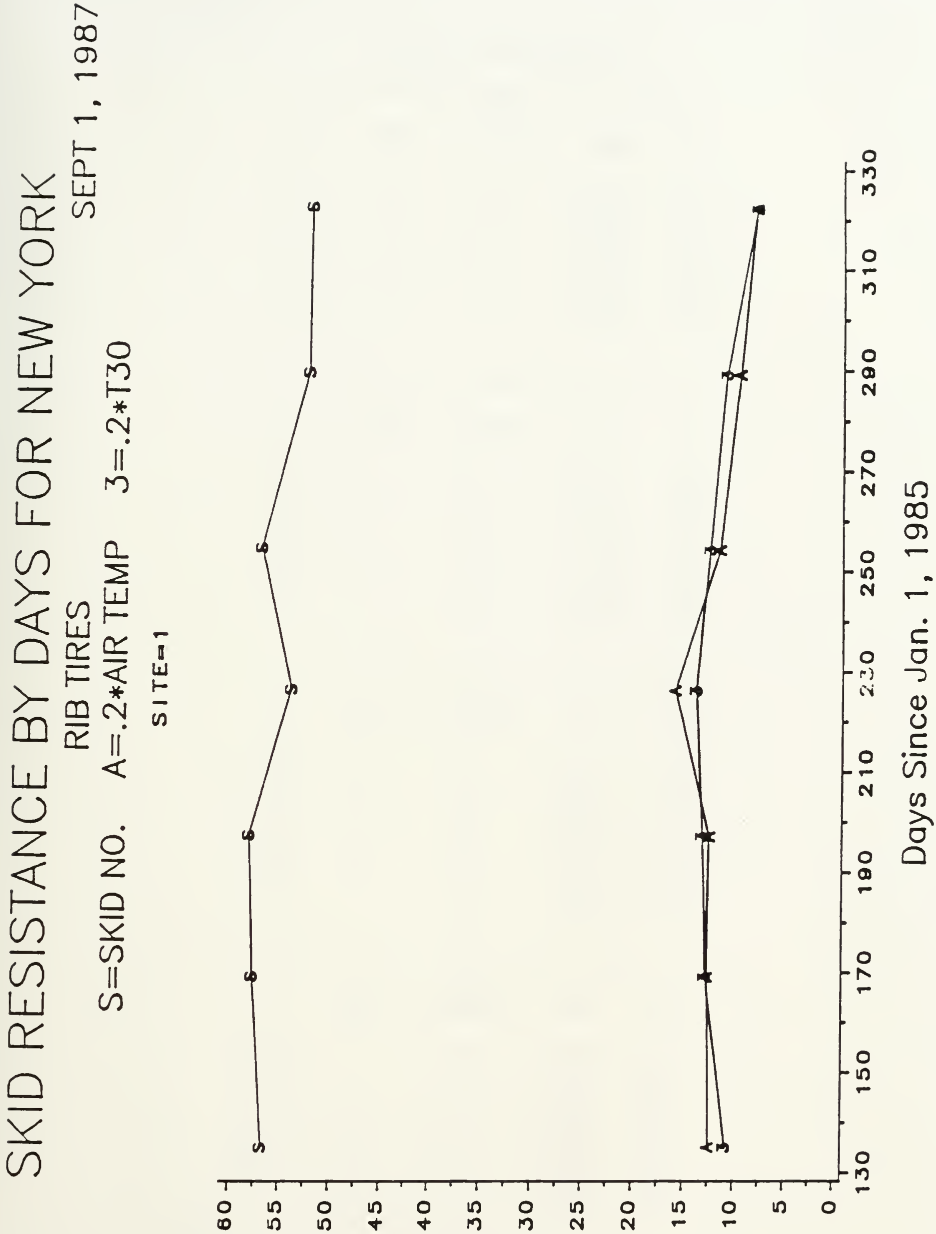
SKID DATA FOR FLORIDA

--------------- SITE=1 ---------------

DAY	SN	AIRTEMP	DSFN	T30
280	31.9	58	2	75.0
311	28.1	78	4	72.0
343	27.3	62	7	65.3
374	31.0	50	0	50.7
402	28.4	70	0	53.8
409	29.9	42	2	54.8
430	25.5	40	2	55.9
462	24.2	75	7	64.0
492	23.3	88	7	67.6
526	25.4	80	5	76.8
560	23.2	85	0	79.1
584	27.5	97	2	80.3
616	30.4	75	3	78.3
644	28.2	78	6	75.7
708	34.6	70	2	65.3

--------------- SITE=2 ---------------

DAY	SN	AIRTEMP	DSFN	T30
280	44.8	58	2	75.0
311	42.0	78	4	72.0
343	43.8	62	7	65.3
374	44.2	50	0	50.7
402	41.9	70	0	53.8
409	44.6	42	2	54.8
430	39.7	40	2	55.9
462	40.1	75	7	64.0
492	39.3	88	7	67.6
526	38.7	80	5	76.8
560	38.4	85	0	79.1
584	40.3	97	2	80.3
616	42.5	75	3	78.3
644	43.2	78	6	75.7
708	45.4	70	2	65.3



SKID RESISTANCE BY DAYS FOR NEW YORK
RIB TIRES
SEPT 1, 1987
S=SKID NO.
A=.2*AIR TEMP
3=.2*T30
SITE=1
60
55
50
45
40
35
30
25
20
15
10
5
0
130
150
170
190
210
230
250
270
290
310
330
Days Since Jan. 1, 1985

SKID DATA FOR NEW YORK

--------------- SITE=1 ---------------

SN	DSFN	AIRTEMP	T30	DAY
56.7	0	62	53.71	135
57.7	2	63	63.97	169
58.1	3	62	65.56	197
53.9	3	79	68.69	226
57.0	6	57	61.90	254
52.3	2	47	53.93	289
52.1	7	39	38.84	322

--------------- SITE=2 ---------------

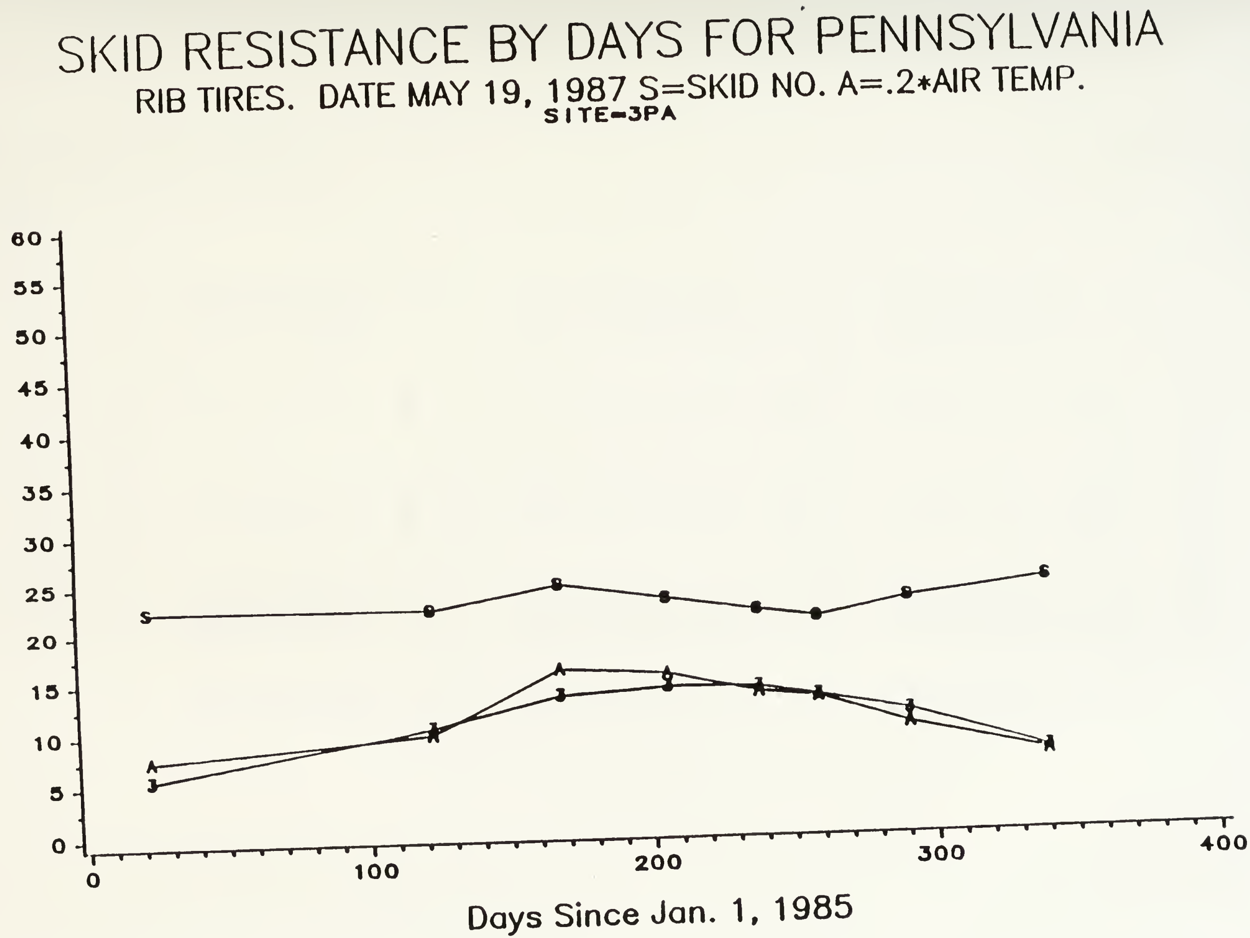
SN	DSFN	AIRTEMP	T30	DAY
54.7	0	62	53.71	135
55.8	2	63	63.97	169
51.2	3	62	65.56	197
52.8	3	79	68.69	226
51.0	6	79	61.90	254
52.4	2	48	53.93	289
50.4	7	39	38.84	322

--------------- SITE=3 ---------------

SN	DSFN	AIRTEMP	T30	DAY
36.8	0	62	53.71	135
40.8	2	63	63.97	169
40.9	3	63	65.56	197
37.6	3	80	68.69	226
37.2	6	83	61.90	254
36.8	2	48	53.93	289
36.0	7	39	38.84	322

--------------- SITE=4 ---------------

SN	DSFN	AIRTEMP	T30	DAY
45.1	0	62	53.71	135
45.0	2	65	63.97	169
47.1	3	64	65.56	197
45.1	3	81	68.69	226
39.5	6	80	61.90	254
44.3	2	49	53.93	289
42.2	7	40	38.84	322


SKID RESISTANCE BY DAYS FOR PENNSYLVANIA
RIB TIRES. DATE MAY 19, 1987 S=SKID NO. A=.2*AIR TEMP.
SITE=3PA
60
55
50
45
40
35
30
25
20
15
10
5
0
0
100
200
300
400
Days Since Jan. 1, 1985

SKID DATA FOR PENNSYLVANIA

--------------- SITE=3 ---------------

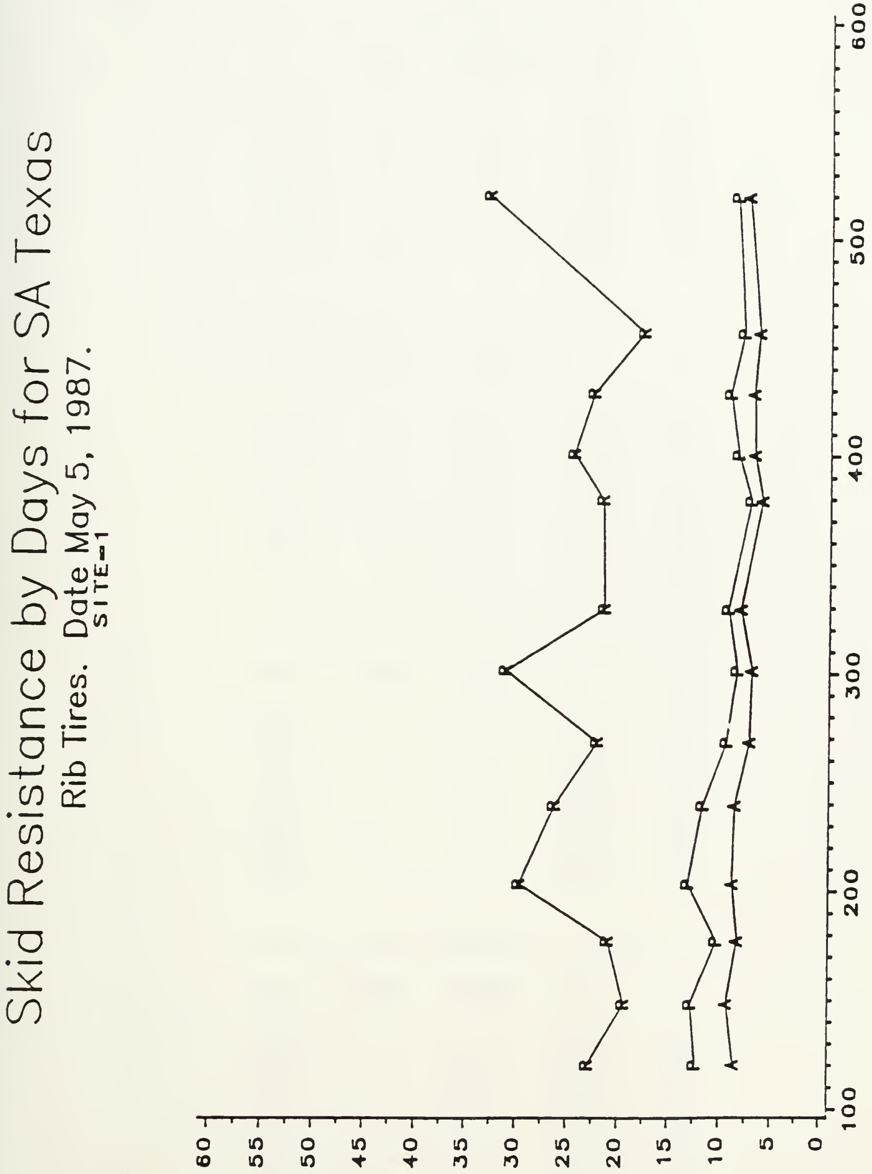
SN	DSFN	AIRTEMP	T30	DAY
22.4	1	37	27.5	22
22.2	7	48	51.3	122
24.6	1	79	66.1	167
23.0	3	76	69.5	205
21.6	1	66	68.7	237
20.7	4	63	63.8	258
22.7	4	49	55.6	290
24.4	2	34	35.6	339

--------------- SITE=4 ---------------

SN	DSFN	AIRTEMP	T30	DAY
27.6	1	37	27.5	22
23.2	1	35	24.6	33
23.6	7	48	51.3	122
24.7	1	62	59.7	143
29.8	0	67	60.8	148
24.8	1	79	66.1	167
23.1	3	76	69.5	205
24.1	1	66	68.7	237
23.1	4	66	63.8	258
23.0	4	48	55.6	290
27.3	2	34	35.6	339

--------------- SITE=5 ---------------

SN	DSFN	AIRTEMP	T30	DAY
35.8	1	37	27.5	22
23.6	7	48	51.3	122
33.5	1	79	66.1	167
31.2	3	75	69.5	205
30.7	1	65	68.7	237
30.4	4	63	63.8	258
31.2	4	48	55.6	290
37.3	2	34	35.6	339


Skid Resistance by Days for SA Texas
Rib Tires. Date May 5, 1987.
SITE=1
Days Since Jan. 1, 1985
100
200
300
400
500
600
0
5
10
15
20
25
30
35
40
45
50
55
60
R
P
A

SKID DATA FOR SAN ANGELO

---------------- SITE=1 ----------------

SN	DSFN	AIRTEMP	T30	DAY
22.90	2	86	66.2	120
19.40	6	93	72.4	148
20.98	7	83	78.2	177
29.68	0	88	78.1	203
26.28	0	86	78.1	239
22.10	7	72	75.5	268
31.08	3	70	65.4	301
21.46	7	81	56.6	329

---------------- SITE=2 ----------------

SN	DSFN	AIRTEMP	T30	DAY
31.18	2	85	66.2	120
32.84	6	92	72.4	148
34.94	7	83	78.2	177
37.74	0	88	78.1	203
34.34	0	86	78.1	239
32.62	7	71	75.5	268
36.46	3	68	65.4	301
29.96	7	80	56.6	329

---------------- SITE=3 ----------------

SN	DSFN	AIRTEMP	T30	DAY
35.84	2	86	66.2	120
32.84	6	94	72.4	148
39.12	7	81	78.2	177
36.64	0	81	78.1	203
31.86	0	85	78.1	239
29.10	7	71	75.5	268
30.38	3	69	65.4	301
27.60	7	80	56.6	329

---------------- SITE=4 ----------------

SN	DSFN	AIRTEMP	T30	DAY
40.54	1	87	66.2	120
37.90	5	96	72.4	148
44.52	7	81	78.2	177
46.84	0	88	78.1	203
43.50	0	92	78.1	239
40.34	7	71	75.5	268
40.92	7	71	65.4	301
38.04	7	81	56.6	329

APPENDIX H

ESTIMATE OF ERROR IN SKID-TESTING (FROM MEYER, ET AL. [13])

APPENDIX I

FRICTION TEST REGRESSION AND SPEED CORRECTION FORMULAS BASED ON CALIBRATION AT TTI (LEFT WHEEL) (FROM TEXAS TRANSPORTATION INSTITUTE [20])

FRICTION TEST REGRESSION AND SPEED CORRECTION FORMULAS BASED ON CALIBRATION AT TTI (LEFT WHEEL) (FROM TEXAS TRANSPORTATION INSTITUTE [20])

1982	FN_{Adj}	=	$[0.21\ (S_p - 40) + FN_{Unadj}]\ 0.907 + 1.6$
1985	FN_{Adj}	=	$[0.16\ (S_p - 40) + FN_{Unadj}]\ 0.993 + 0.8$
1987	FN_{Adj}	=	$[0.23\ (S_p - 40) + FN_{Unadj}]\ 0.918 + 1.7$
1989	FN_{Adj}	=	$[0.21\ (S_p - 40) + FN_{Unadj}]\ 0.990 + 0.3$

APPENDIX J

MODEL SKID ACCIDENT REDUCTION PLAN (FROM FHWA [31])

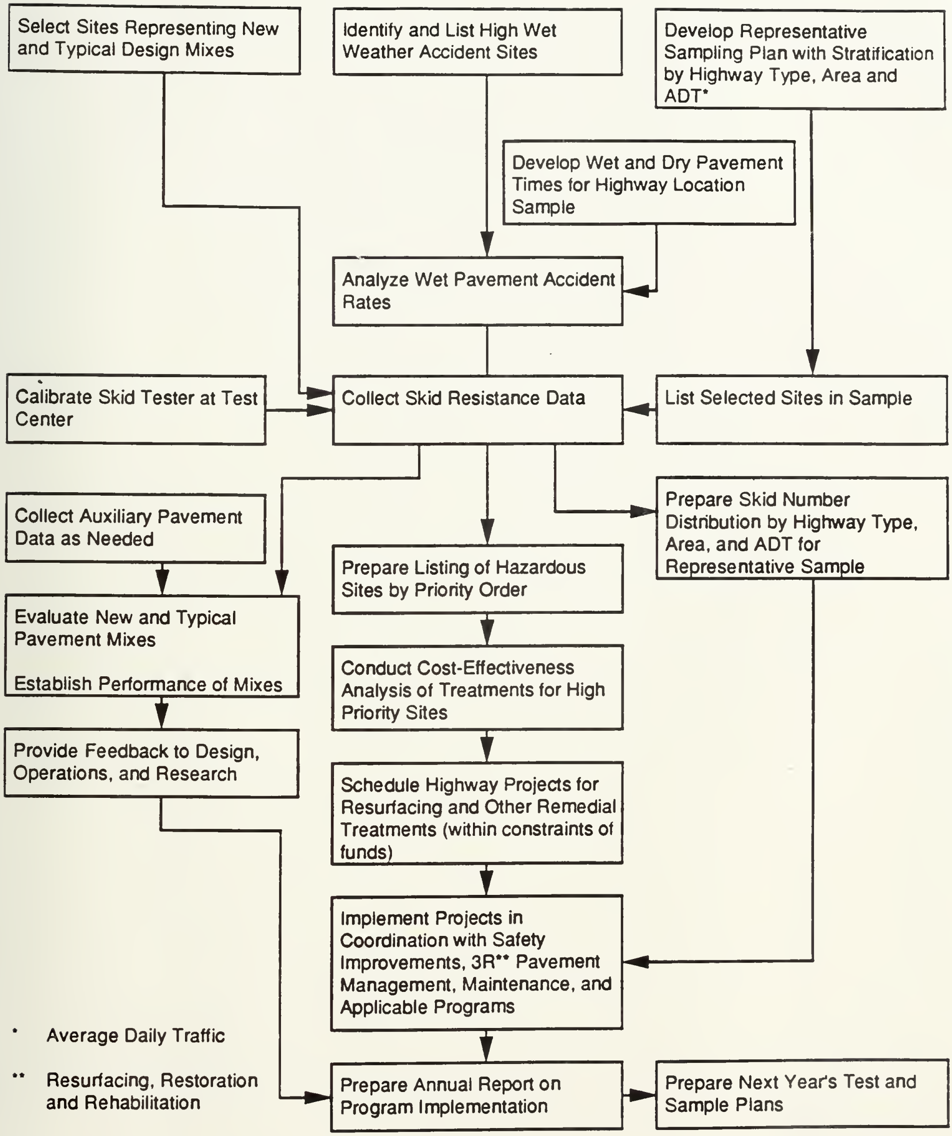


Figure J-1. Model Skid Accident Reduction Plan